Master's Degree Thesis

ISRN: BTH-AMT-EX--2006/D-05--SE

Characterization of a Cylinder Liner Surface by Roughness Parameters Analysis

Zlate Dimkovski

Department of Mechanical Engineering
Blekinge Institute of Technology
Karlskrona, Sweden
2006

Supervisor: Ansel Berghuvud, Ph.D. Mech. Eng.

Characterization of a cylinder liner surface by roughness parameters analysis

Zlate Dimkovski

Department of Mechanical Engineering
Blekinge Institute of Technology
Karlskrona, Sweden

2006

Thesis submitted for completion of Master of Science in Mechanical Engineering with emphasis on Structural Mechanics at the Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden.

Abstract:

Cylinder liner surface topology greatly affects oil consumption and wear of engines. Surface optimization would be greatly facilitated by automatic quality control. Surface roughness definitions, parameters, and measurement techniques were reviewed and samples of different Volvo truck engine cylinder liner types were measured. Routines for extracting and computing groove parameters, useful in the automation of quality control in production, were developed, implemented in MATLAB and applied on the samples. The principles of the last two steps procedures needed to fully automate the surface grading by roughness parameters analysis were described.

Keywords:

Cylinder Liner Surface, Roughness Parameters, GOETZE Honing Guide, MATLAB, Quality Control Method.

Acknowledgements

I want to thank to all the people who helped me to carry out this final year project and so to go trough this unique experience. I thank to the following persons:

Mr. Bengt-Göran Rosén for his warm welcome to the Halmstad Högskola, his kindness, his time he dedicated me, and of course for the knowledge he gave me in the Surface Roughness field,

Mr. Ansel Berghuvud from the Blekinge Tekniska Högskola in Karlskrona, who helped me to follow-up my project and for his suggestions and comments,

Mr. Robert Ohlsson for his instructions, suggestions and comments, and together with Mr. Staffan Johansson I thank them for their warm reception and the realization of the interesting visit of Volvo in Göteborg,

Mr. Mats Gunnarsson for his instructions, suggestions and analysis in Mathematical Statistics,

Mr. Stefan Rosén from Toponova AB for his instructions and guidance in performing optimal measurements on the stylus and interferometer,

Mr. Frederic Cabanettes, my colleague and associate in this global project, for his help, his cooperation and his company,

Ms. Suzana Maricic for reading and checking of the report, and for all the support she gave me.

Karlskrona, January 2006

Zlate Dimkovski

Contents

1 Notation

A_2	'Valley area' of the material ratio curve	[µm]
a	Coefficient of the Least Squares Mean Plane;	
	Groove width	[mm]
b	Coefficient of the Least Squares Mean Plane	
C	Groove height	[µm]
c	Coefficient of the Least Squares Mean Plane	
c_1	Height of the upper threshold of the Number of Peaks	[µm]
c_2	Depth of the lower threshold of the Number of Grooves	[µm]
D	Profile peak count	
DR	Dispersion Range	[%]
d	Distance between grooves	[mm];
	Total derivative	
$h_{0.8}$	Height at the 80% of the surface material ratio	[µm]
k	The *k*-th (arbitrary) number of summits	
L	Evaluation length	[mm]
l	Sampling length	[mm]
M	Mean combination vector; Total number of data points in *x*-direction	
Mr1	Bearing Ratio at Peak to Core Transition	[%]
Mr2	Bearing Ratio at Core to Valley Transition	[%]
m	The *m*-th data point in *x*-direction; Mean value	
n	The concerned number of grooves	
N	Total number of data points in *y*-direction	
P	Primary profile	
p	Peak	

R	Roughness profile and Roughness parameters in 2D	
S	Roughness Parameters in 3D	
sigma	Standard deviation	
SV2	Valley void volume parameter	[mm^3]
t_{pa}	Bearing ratio percentage parameter for an unfiltered profile	[%]
Vvv	Valley void volume parameter	[mm^3]
v	Valley	
W	Waviness Profile and parameters in 2D	
x	*x*-axis (abscissa of the horizontal and of the vertical plane); Values of the considered parameter	
y	*y*-axis (ordinate of the horizontal plane)	
z	*z*-axis (ordinate of the vertical plane); Original surface	
Δ	Sampling interval	[µm]
η	Residual surface	

Indices

a	Average roughness
ds	Density of summits
hsc	High spot count
i	The *i*-th data point in *x*-direction; The *i*-th measurements
j	The *j*-th data point in *y*-direction
k	Kernel (Core) Roughness Depth
mr1	Bearing Ratio at Peak to Core Transition
mr2	Bearing Ratio at Core to Valley Transition
n	Total number of measurements
p	Peak roughness, i.e. height of the highest peak
pk	Reduced peak height

t	Total roughness (Total Peak-to-Valley Height)
v	Valley roughness, i.e. depth of the deepest valley
vk	Reduced valley depth
x	Data in x-direction
y	Data in y-direction

Abbreviations

FG	Final Grade
IG	Interim Grade
LCL	Lower Control Limit
SEM	Scanning Electronic Microscope
UCL	Upper Control Limit

2 Introduction

The development of engines today is driven by legislation demands and especially particulate levels will be difficult to achieve for the next generations of Internal Combustion Engines. Oil consumption is a major contributor to these particulates and must therefore be decreased. Other concerns are fuel consumption, longevity and wear of engines which involve decreasing friction in the engine. All these demands are to a great extent controlled by the topography of the cylinder liner surface. In order to optimize surfaces, it is therefore primordial to use a reliable method to characterize them.

A comprehensive method is described in the GOETZE Honing Guide [1], based on: Roughness Parameters (Profile) Analysis giving information along *x* and *z* axis and Image Analysis of Scanning Electronic Microscope (SEM) pictures giving information along *x* and *y* axis (see the Figure 2.1. below). Because it is tedious, subjective and time consuming method done by an expert, the intention is to automate this method and surpass these disadvantages.

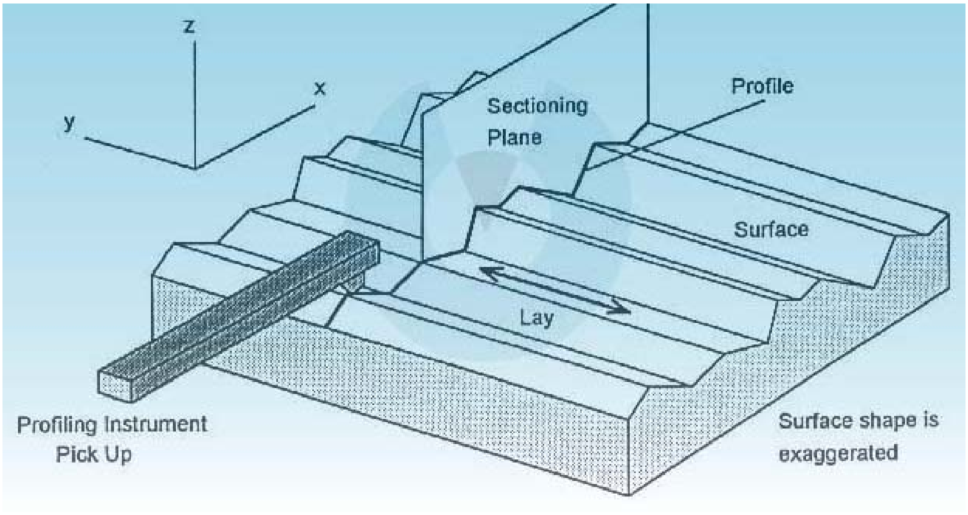


Figure 2.1. Profile: information along x and z axis, SEM pictures: information along x and y axis [2].

This thesis work is a part of an automation of this Quality Control Method doing the Roughness Parameters Analysis. The created MATLAB scripts can be used to find the needed number of measurements per sample and to compute the Grooves Parameters. The studies of the Parameters Grading Criterion and the Determination of the Final Grade are not worked out in detail due to time constraint. Instead the general idea of their procedures is presented.

2.1 Background

The piston is the part of the engine which transmits the energy produced by air fuel mix combustion to the connecting rod. In this way the straight movement (piston sliding along cylinder liner) is changed into circular movement by the way of the crankshaft. For sealing, piston rings encircle piston. Each piston ring has its own use: the bottom piston ring ensures that the supply of lubrication oil is evenly deposited on the cylinder walls; the intermediate ring acts as wiper ring to remove and control the amount of oil film on the cylinder walls; the top ring control the engine compression. In that case it can be easily seen how important is the tribological system cylinder/piston ring (see the Figure 2.2.) bearing in mind that it represents around 35% of energy losses in an engine. Nowadays one of the research fields for manufacturers is the improvement of the Cylinder Liner Surface quality.

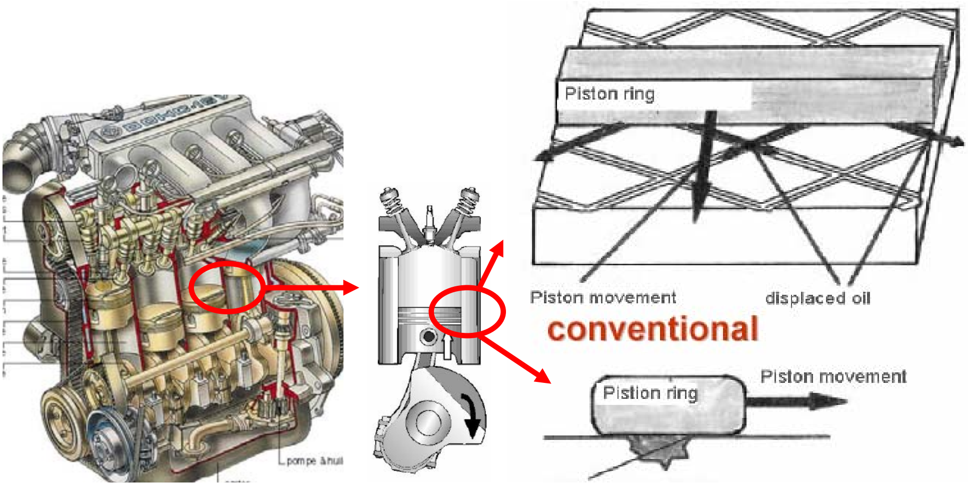


Figure 2.2. Global view of an engine; Piston/Cylinder Interface; Tribological system: Piston ring/Cylinder [3].

2.1.1 The Ideal Cylinder Liner Surface

It is found that, the ideal Cylinder Liner Surface should have the following properties:

- Smooth surface to reduce friction and easily adjusting of the running clearance.
- Important contact area to share wear all along the surface and to avoid high pressure zones but also for sealing.
- Deep grooves for lubrication retention and debris collection.

So, the machining called *plateau honing* is perfectly adapted to the situation. From the Figures 2.3 and 2.4 the smoothness on the top and the deep grooves underneath can be seen.

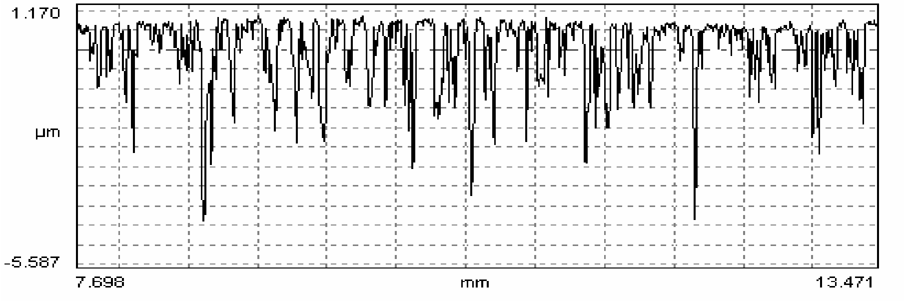


Figure 2.3. Profile of a plateau honed surface from a Volvo truck engine.

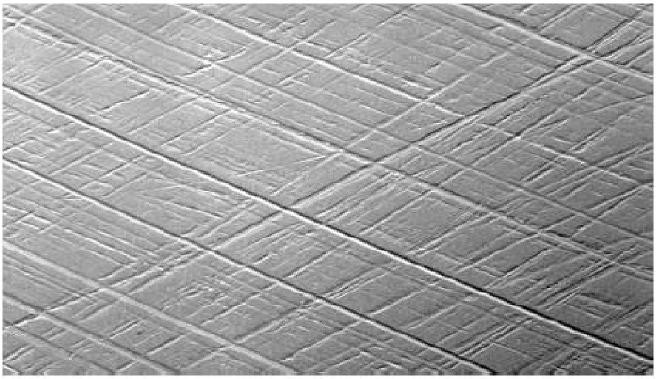


Figure 2.4. SEM picture of a plateau honed surface [4].

2.1.2 The Real Cylinder Liner Surface

Because of the machining conditions there are several deviations from good commercial finish, which are presented in the table 2.1 below.

Table 2.1. Summary of most common deviations-Their Cause and Effect.

DEFAULT	EFFECT ON ENGINE PERFORMANCE	COMMON MAJOR CAUSES
Wide, deep cross hatch grooves	Causes abnormal wear, excessive oil consumption	Stone grit too coarse, poor stone breakdown, coolant viscosity too high, excessive stone pressure
Cross hatch grooves irregularly spaced	Poor oil distribution	Stone grade too hard, stone grit too coarse, poor stone breakdown
Cross hatch grooves fragmented	Slows ring, causes scratching and high wear, lowers life and oil economy, raises ring temperature, causes excessive variation engine to engine	Insufficient dwell strokes at end of honing cut, stone grit too coarse
One directional cut cross hatch	Causes ring rotation, rapid wear	Excessive play in hone components, such as joints, or stone holder to body clearance
Low cross hatch angle	Poor oil distribution, high impact forces on rings, excessive wear, shortens life	Tool kinematics
Particles embedded in surface	Slows ring, causes scratching and high wear, lowers life and oil economy, raises ring temperature, causes excessive variation engine to engine	Poor stone breakdown and cutting action, low coolant volume
Blechmantel	Particles in oil and fuel	Diamond honing, poor stone breakdown

2.2 Purpose and Problem description

The purpose of this thesis work is to automate the characterization of a Cylinder Liner Surface, doing a Roughness Parameters Analysis. In parallel with this work, a thesis work dealing with an Image Analysis is active. The both thesis works need to cover the Quality Control method described in the GOETZE Honing Guide [1], which can be summarized in the following block diagram:

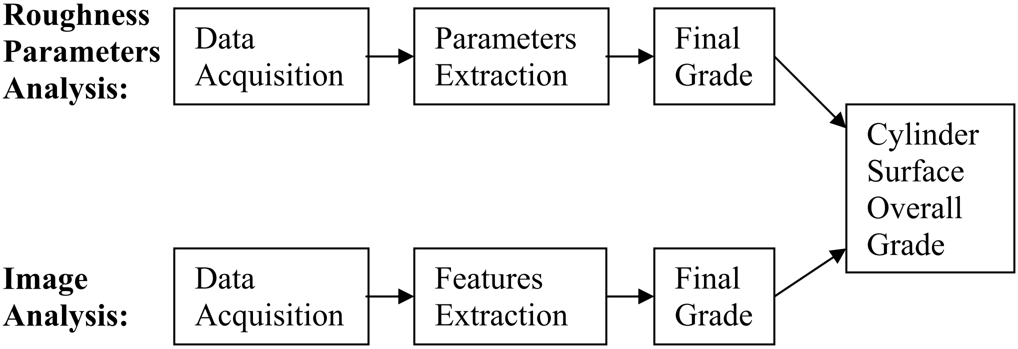


Figure 2.4. Block Diagram of the Quality Control Method.

The Roughness Parameters Analysis and the Image Analysis are to end up with Final Grades (see Figure 2. 4), so that the lower Final Grade is to be the Overall Grade of the Cylinder Liner Surface.

Regarding the Roughness Parameters Analysis, there are five GOETZE defined Parameters. Two of them are standardized parameters and they can be easily computed in the measuring software. The other three parameters are Groove parameters and they can not be computed in any roughness software.

Six different Cylinder Liner Types from Volvo Truck engines are given to be examined. Three samples of each are to be taken.

Hence the Characterization of a Cylinder Liner Surface by Roughness Parameters Analysis can be summarized in the following steps:

1. Measure and study how many measurements are needed per sample.

2. Measure the samples and compute the standardized parameters in the measuring software.
3. Compute the Groove parameters in MATLAB.
4. Study the Grading Criterion for each GOETZE defined parameter.
5. Determine the Final Grade

When the above steps are to be completed and obtained the Final Grade of an examined surface, it is desirable to see if the values of other roughness parameters which are not included in this method are related with those which are included. This implies performing measurements by different techniques and computing other 2D and 3D parameters.

2.3 Related work

Today there are plenty of information about the Surface Roughness found in the publications and guides [2, 5, 6, 10, and 12].

Regarding the Cylinder Surface Roughness, important information can be found in the GOETZE Honing Guide [1], in the paper of Mark C. Malburg [4], and in the publication of J. Beyerer, D. Krahe and F. Puente Leon [7].

A comprehensive study of how many measurements are needed for roughness parameter stability is reached, is presented by R. Ohlsson, B. G. Rosen and J. Westberg [9], and in the thesis work of E.Lardon and F. Lopez [11].

For a determination of the Control Limits in the study of the Parameter Grading Criterion, it is used the X Control Chart method, found in the publication of D. C. Montgomery, G. C. Runger and N. F. Hubele [13] and in the Statistical Toolbox of MATLAB.

Nowadays many researchers are trying to solve the problem of automating the characterization of a Cylinder Liner Surface. One alternative method is to use a Neural Network. E. Mainsah and D. T. Ndumi [8] used this approach and showed that the surface can be classified once the system is trained, meaning that it is still needed an expert to give an input in the system. Another study is done by J. Beyerer, D. Krahe and F. Puente Leon [7] using image processing method, which gives no depth information.

2.4 Report structure

This report starts with some basic definitions, techniques and instruments used in the field of a Surface Roughness, described in the Chapter 3.

The Chapter 4 presents the experimental part of this project, mainly carried out in the lab of Toponova AB. Here the first two steps mentioned in the Problem description are encompassed. The first step is: Determination of the needed number of measurements; and the second: Measurements and Computation of the standardized parameters.

Chapter 5 is the post-experimental part, the part of Grading Analyses. It covers the rest of the steps mentioned in the Problem description. The third step is named as: Groove parameters analysis; the fourth: Grading factor analysis; and the fifth: Determination of the final grade.

Finally, the Chapter 6 summarizes the main conclusions and discussions of this work.

3 Surface roughness

This chapter includes the basic theory about the Surface Roughness. Section 3.2 presents the definitions of some standardized roughness parameters used in the practice today. In the Section 3.3 the measurement techniques and instruments used in this project are shortly described.

3.1 Basic definitions

3.1.1 Tribology

Tribology is defined as the science of interacting surfaces in relative motion. The word *tribology* comes from the Greek *tribos*, meaning rubbing. In any machine there are many component parts that operate by rubbing together. Some examples are bearings, gears, cams and tappets, tyres, brakes, and piston rings. All of these components have two surfaces which come into contact, support a load, and move with respect to each other. Sometimes it is desirable to have low friction, to save energy, or high friction, as in the case of brakes. Usually we don't want the components to wear, hence they are lubricated.

The study of friction, wear, lubrication and contact mechanics are all important parts of tribology. Related aspects are surface engineering (the modification of a surface to improve its function, for example by applying a surface coating), *surface roughness*, and rolling contact fatigue (where repeated contacts cause fatigue to occur).

3.1.2 Surfaces

Surface

A *surface* is a boundary that separates an object from another object or substance.

Nominal Surface

A *nominal surface* is the intended surface. The shape and extent of a nominal surface are usually shown and dimensioned on a drawing. The nominal surface does not include intended surface roughness.

Real Surface

A *real surface* is the actual boundary of an object. It deviates from the nominal surface as a result of the process that created the surface. The deviation also depends on the properties, composition, and structure of the material that the object is made of.

Measured Surface

A *measured surface* is a representation of the real surface obtained with some measuring instrument. This distinction is made because no measurement will give the exact real surface.

Surface geometry

Surface geometry and geometric dimensioning and defining of the tolerances are large subfields of metrology which parallel or exceed surface finish in scope and complexity. This is the realm of coordinate measuring machines and roundness measuring instruments and contouring instruments. However, there is an increasing overlap between geometric measurements and surface finish measurements, so it is helpful to be aware of some basic concepts in geometric measurement.

Form

Form refers to the intentional shape of a surface which differs from a flat line.

Dimension

Dimensions are the macroscopic sizes of a part, e.g. diameter or length.

Tolerance

A *tolerance* is an allowable range for a dimension to take, a specified interval of dimensions where the part will still function acceptably.

Surface Finish Imperfections:

Form Error

Form Error encompasses the long wavelength deviations of a surface from the corresponding nominal surface. Form errors result from large scale problems in the manufacturing process such as errors in machine tool ways, guides, or spindles, insecure clamping, inaccurate alignment of a work-piece, or uneven wear in machining equipment. Form error is on the dividing line in size scale between geometric errors and finish errors.

Texture

Surface *texture* is the combination of fairly short wavelength deviations of a surface from the nominal surface. *Texture* includes roughness, waviness, and lay, that is, all of the deviations that are shorter in wavelength than form error deviations.

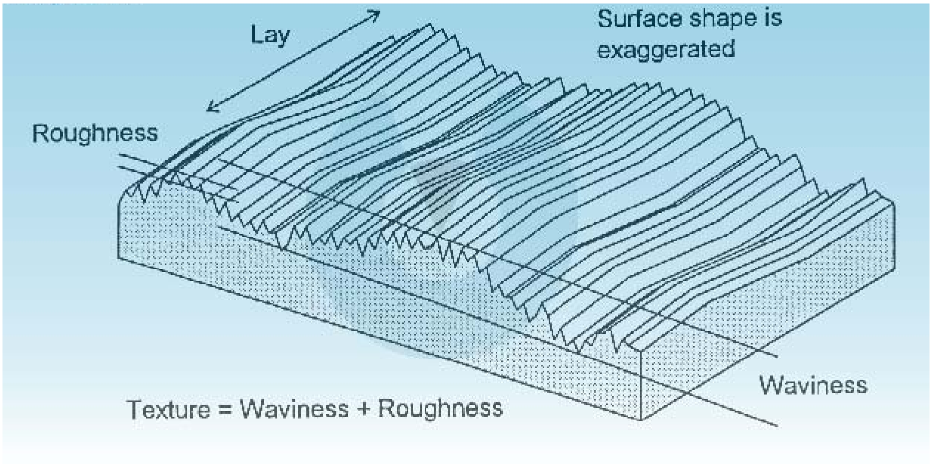


Figure 3.1. Surface Finish Imperfections [2].

Roughness

Roughness includes the finest (shortest wavelength) irregularities of a surface. Roughness generally results from a particular production process or material condition.

Waviness

Waviness includes the more widely spaced (longer wavelength) deviations of a surface from its nominal shape. Waviness errors are intermediate in wavelength between roughness and form error. Note that the distinction between waviness and form error is not always made in practice, and it is not always clear how to make it. New standards are emerging that define this distinction more rigorously.

Lay

Lay refers to the predominant direction of the surface texture. Ordinarily *lay* is determined by the particular production method and geometry used. Turning, milling, drilling, grinding, and other cutting tool machining processes usually produce a surface that has lay: striations or peaks and valleys in the direction that the tool was drawn across the surface. The shape of the *lay* can take several forms. Other processes produce surfaces with no characteristic direction: sand casting, peening, and grit blasting. Sometimes these surfaces are said to have a non-directional, particulate, or protuberant *lay*. *Lay* (or the lack thereof) is important for optical properties of a surface. A smooth finish will look rough if it has a strong *lay*. A rougher surface will look more uniform if it has no *lay* (it will have more of a matte look).

Flaws

Flaws are unintentional and unwanted problems with a surface. Usually the term *flaw* refers to individual and unusual features such a: scratches, gouges, burrs, etc.

3.1.3 Surface Profiles

Profile

A *profile* is, mathematically, the line of intersection of a surface with a sectioning plane which is (ordinarily) perpendicular to the surface. It is a two-dimensional slice of the three-dimensional surface. Almost always *profiles* are measured across the surface in a direction perpendicular to the lay of the surface.

Nominal Profile

The *nominal profile* is the straight or smoothly curved line of intersection of the nominal surface with a plane which is (ordinarily) perpendicular to the surface. The *nominal profile* has a known mathematical shape for a known part (most often a straight line or a circle).

Real Profile

A *real profile* is a profile of the real surface. It is the (idealized) shape of the intersection of a surface with a perpendicular sectioning plane.

Measured Profile

A *measured profile* is a representation of the real profile obtained with some measuring instrument. This distinction between "real" and "measured" is made because no measurement will give the exact real surface.

Modified Profile

A *modified profile* is a measured profile that has been modified by mechanical, electrical, optical, or digital filtering. The filtering is ordinarily done to minimize certain surface characteristics while emphasizing others. A *modified profile* differs from a *measured profile* in the sense that the real profile is intentionally modified as part of the measurement. The details of the modification are typically selectable by the user of an instrument. A *measured profile* is an unintentional modification of the real profile resulting from the limitations of the measuring instrument.

Traced Profile

An instrument's raw trace of a surface is always relative to some reference plane. The *traced profile* is the raw measured profile with profile height measured relative to a zero line which is parallel to the instrument's reference plane. Since an instrument's set-up will vary from measurement to measurement, the traced profile has little value except as the starting point for leveling or other form removal.

Form Profile

The *form profile* is the nominal profile in the coordinate system of the traced profile. That is, it is the nominal shape of the part relative to the reference line of the profiling instrument. Ordinarily form will be a straight line or a circle. It is most often found by a least squares fit of the traced profile with a straight line or a circle.

Primary Profile-P

The *primary profile* is the traced profile altered by subtracting the form. The primary profile is thus the sum of all the deviations of the measured profile from the nominal profile (see Figure 3.3). The *primary profile* is the sum of the form error profile, the waviness profile, and the roughness profile. Often the *primary profile* is referred to as the "unfiltered profile" or the "total profile". In this case, it is the trace of the surface leveled and magnified, but otherwise unmodified.

Wavelength

Wavelength (almost universally denoted X) refers to the repeat length of a periodic function (see Figure 3.2).

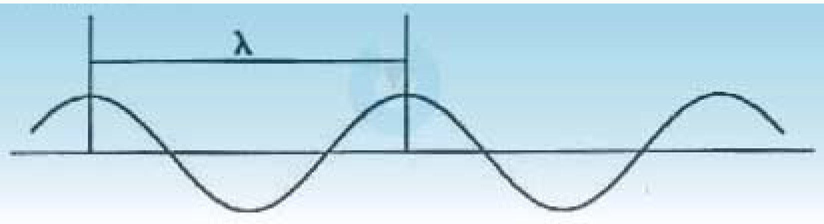


Figure 3.2. Wavelength is the distance between similar points of a repeating, periodic signal [2].

A real profile can be thought of as the sum of many different individual functions, each with its own *wavelength*.

Filter

A *filter* (for purposes of surface finish measurement) is an electronic, mechanical, optical, or mathematical transformation of a profile to attenuate (remove) wavelength components of the surface outside the range of interest for a measurement.

Form Error Profile

The *form error profile* encompasses the very long wavelength deviations of the traced profile from the nominal profile. *Form error* is the modified profile obtained by filtering the measured profile to attenuate medium and short wavelength components associated with waviness and roughness.

Texture Profile

The *texture profile* is the sum of the waviness profile and the roughness profile, i.e. the remaining medium and short wavelength deviations of the measured profile from the nominal profile after form error has been subtracted from the primary profile (see Figure 3.3). Measurement of texture is the primary domain of traditional surface finish analysis.

Waviness Profile-W

The *waviness profile* includes medium wavelength deviations of the measured profile from the nominal profile. The waviness is the modified profile obtained by filtering a measured profile to attenuate the longest and shortest wavelength components of the measured profile (i.e. the filter removes form error and roughness, see Figure 3.3).

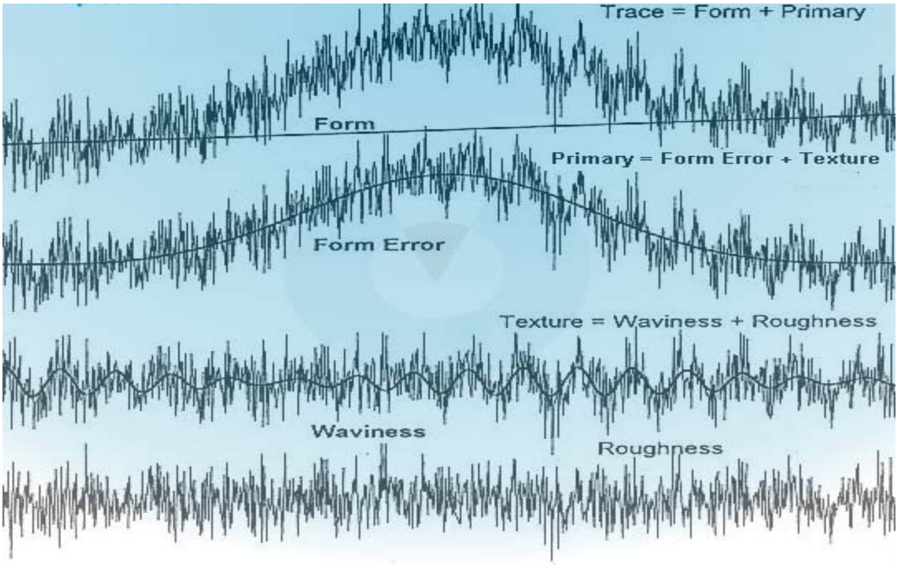


Figure 3.3. An important concept in surface finish is the breaking of a surface profile into different components by wavelength [2]. There is a hierarchy of components, as shown.

Roughness Profile-R

The *roughness profile* includes only the shortest wavelength deviations of the measured profile from the nominal profile. The *roughness profile* is the modified profile obtained by filtering a measured profile to attenuate the longer wavelengths associated with waviness and form error (see Figure 3.3). Optionally, the *roughness* may also exclude (by filtering) the very shortest wavelengths of the measured profile which are considered noise or features smaller than those of interest.

Roughness is of significant interest in manufacturing because it is the *roughness* of a surface (given reasonable waviness and form error) that determines its friction in contact with another surface. The *roughness* of a surface defines how that surfaces feels, how it looks, how it behaves in a contact with another surface, and how it behaves for coating or sealing. For moving parts the *roughness* determines how the surface will wear, how well it will retain lubricant, and how well it will hold a load.

3.1.4 Surface Profile Filtering

A surface profile may be composed of a range of frequency components. The high frequency (or short wave) components correspond to those that are perceived to be rough and hence called "roughness". The low frequency (or long wave) components correspond to more gradual changes in the profile and are often associated with the terms "waviness" or even "form". Filtering is a procedure to separate certain frequency components of a surface profile. Depending on what component is desired, the filtering operation may be:

- *Short-pass*, or high-pass - letting the short wavelength (high frequency) components through, therefore the roughness profile is extracted;
- *Long-pass*, or low-pass - letting the long wavelength (low frequency) components through, therefore the waviness profile is extracted;
- *Band-pass* - extracting a profile of specified bandwidth by applying both high-pass and low-pass filters, allowing controlled profile data bandwidth;

The term "cut-off" numerically specifies the frequency bound below or above which the components are extracted or eliminated.

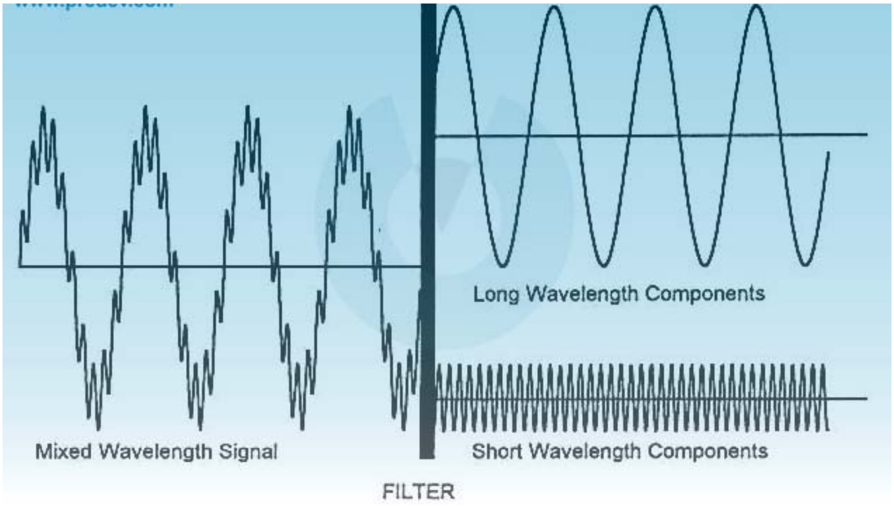


Figure 3.4. Surface Profile Filtering [2].

3.2 Parameters

There are many standardized and not standardized parameters used today. Although there are defined 3D parameters; there is still no accepted standard for 3D characterization. Below is given an overview of the parameters important for characterization of a cylinder liner surface. Some 2D parameters are given together with their 3D equivalents. A few general points should be borne in mind when it is spoken about 3D Parameters:

- Each of them starts with the letter '*S*' rather the '*R*'.
- Unlike 2D Parameters that are obtained using several sampling lengths, all 3D parameters are computed from one area.
- They are evaluated on the residual surface $\eta(x,y)$, which is defined as the surface that is left after the (linear) *least squares mean plane* has been subtracted from the original surface.

$$\eta(x,y)=z(x,y)-(a+bx+cy) \tag{3.1}$$

where $z(x,y)$ represents the original surface, a, b, and c are the coefficients of the *least squares mean plane* [6] and x, y are the coordinates of the data points.

- The total numbers of data points in the x- and y- direction are represented by M and N respectively, with i and j representing indices in the x- and y- direction. The variables l_x and l_y represent the sampling length in the x- and y- direction and Δx and Δy, the sampling interval in the x- and y- direction respectively.

3.2.1 Amplitude Parameters

Average Roughness, R_a/S_a

The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length:

$$R_a = \frac{1}{L}\int |z(x)| dx \qquad [\mu\mathrm{m}] \qquad (3.2)$$

When evaluated from digital data, the integral is normally approximated by a trapezoidal rule:

$$R_a = \frac{1}{M}\sum_{m=1}^{M} |z_m| \qquad [\mu\mathrm{m}] \qquad (3.3)$$

Graphically, the average roughness is the area (see Figure 3.5) between the roughness profile and its centre line divided by the evaluation length (normally five sample lengths with each sample length equal to one cut-off):

Its 3D equivalent is:

$$S_a = \left[\frac{1}{l_x l_y}\int_0^{l_x}\int_0^{l_y} \left|\eta^2(x,y)\right| dxdy\right]^{1/2} \approx \left[\frac{1}{MN}\sum_{j=1}^{N}\sum_{i=1}^{M} \left|\eta^2(x_i,y_j)\right|\right]^{1/2} \quad [\mu\mathrm{m}] \qquad (3.4)$$

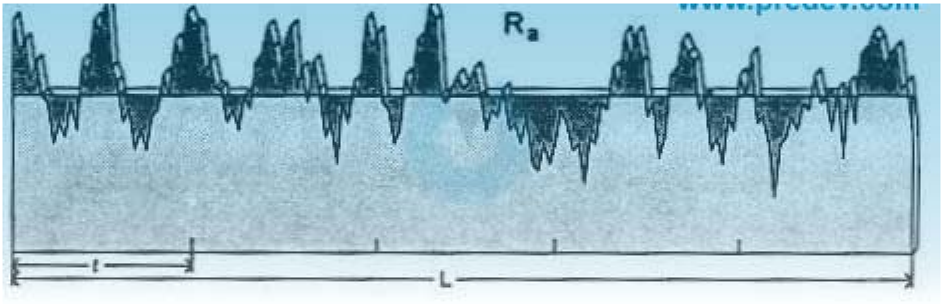


Figure 3.5. The average roughness, R_a, is an integral of the absolute value of the roughness profile. It is the shaded area divided by the evaluation length-L. R_a is the most commonly used roughness parameter [2].

Roughness parameters, R_p, R_v, and R_t

The peak roughness R_p is the height of the highest peak in the roughness profile over the evaluation length (see below p_1 in Figure 3.6). Similarly, R_v is the depth of the deepest valley in the roughness profile over the evaluation length (v_1). The total roughness (or Total Peak-to-Valley Height), R_t, is the sum of these two, or the vertical distance from the deepest valley to the highest peak (see Formula 3.6).

These three extreme parameters will succeed in finding unusual conditions: a sharp spike or burr on the surface that would be detrimental to a seal for example or a crack or scratch that might be indicative of poor material or poor processing.

$$R_p = \left|\max(z(x))\right|,\ R_v = \left|\min(z(x))\right|,\quad 0<x<L \qquad [\mu\text{m}] \qquad (3.5)$$

$$R_t = R_p + R_v \qquad [\mu\text{m}] \qquad (3.6)$$

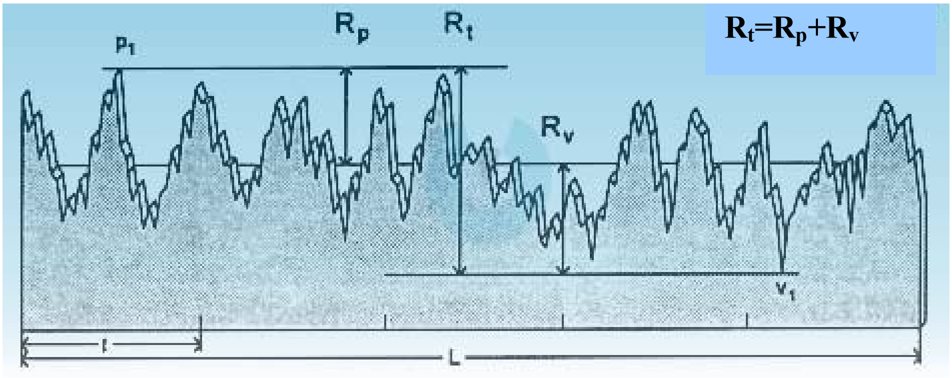


Figure 3.6. Roughness parameter: R_p*,* R_v *and* R_t *[2].*

3D parameters, S_p, S_v, and S_t

The total peak-to-valley height 3D parameter, S_t, is defined as a sum of *the maximum peak height,* S_p, and *the lowest valley depth,* S_v, within the sampling area:

$$S_t = (|S_v| + |S_p|) \qquad [\mu m] \qquad (3.7)$$

3.2.2 Spacing Parameters

Profile peak count, *D* or high spot count, R_{hsc}

R_{hsc}- is the high spot count or the number of peaks over the evaluation length. The R_{hsc}- parameter reports the number of profile crossings above a user defined threshold c_1 (see the Figure 5.1). Often it is called in the project as *'Number of peaks'*, n_p.

Valley count, R_{vc}

R_{vc} is the number of valleys over the evaluation length. The R_{vc} parameter reports the number of profile crossings below a user defined threshold c_2.

The threshold value is positive when above the mean line or negative when below the mean line. Often it is called in the project as 'Number of valleys'.

Density of summits, S_{ds}

S_{ds} is the number of summits of a unit sampling area

$$S_{ds} = \frac{Number\ \ of\ \ summits}{(M-1)(N-1)\cdot \Delta x \cdot \Delta y} \tag{3.8}$$

3.2.3 Bearing Ratio Parameters

Bearing Ratio Percentage, t_p

The symbol t_p has two meanings. First, it is used generically as the abscissa of bearing/material ratio curve (see Figures 3.7 and 3.8), which shows the material ratio as a section height. Second, t_p as a parameter refers to the bearing ratio at a specified height. The most common way of specifying the height is to move over a certain percentage (reference percentage) on the bearing ratio curve and then to move down a certain depth (the slice depth). The bearing ratio at the resulting point is t_p. The purpose of the reference percent is to eliminate spurious high peaks from consideration; these will wear off in early part use. The slice depth then corresponds to an allowable roughness or to a reasonable amount of wear.

Another common way of choosing the height level for t_p is as a distance up or down from the mean line of the roughness profile.

t_{pa} is a notation for a *bearing ratio* for an unfiltered profile. Often is found as *Rmr(c)* (see Figure 3.7).

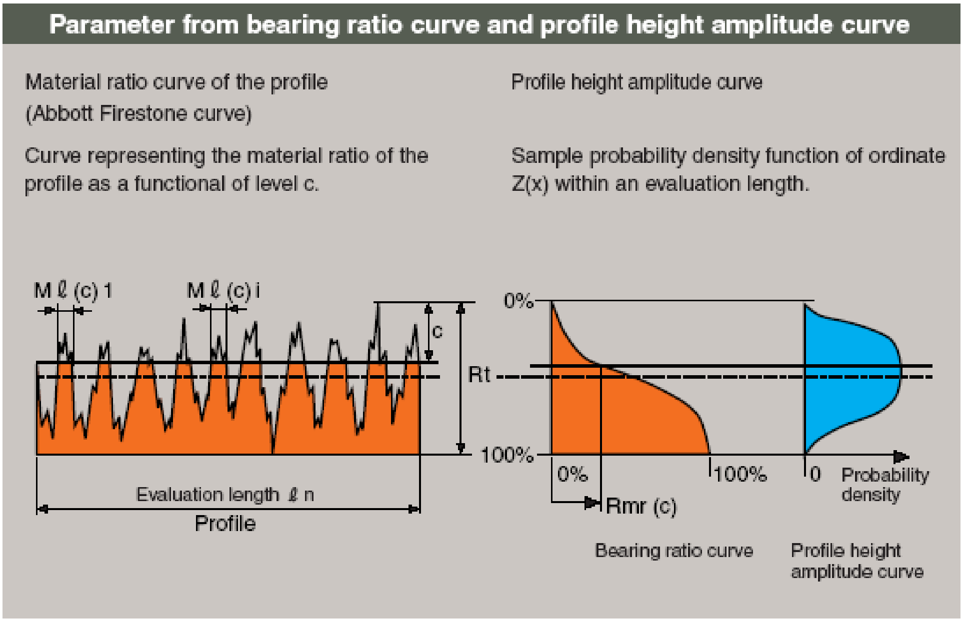


Figure 3.7. Material/bearing ratio curve [12].

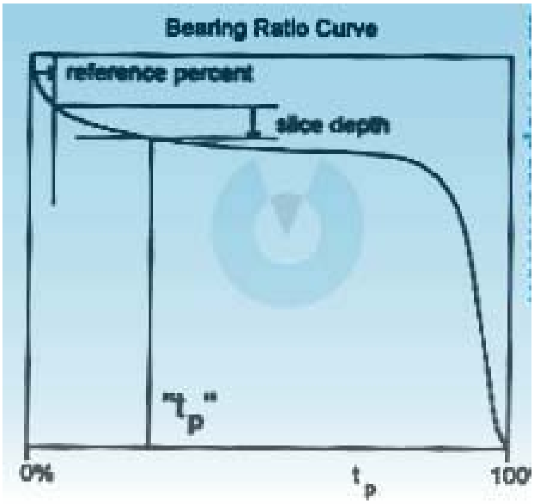
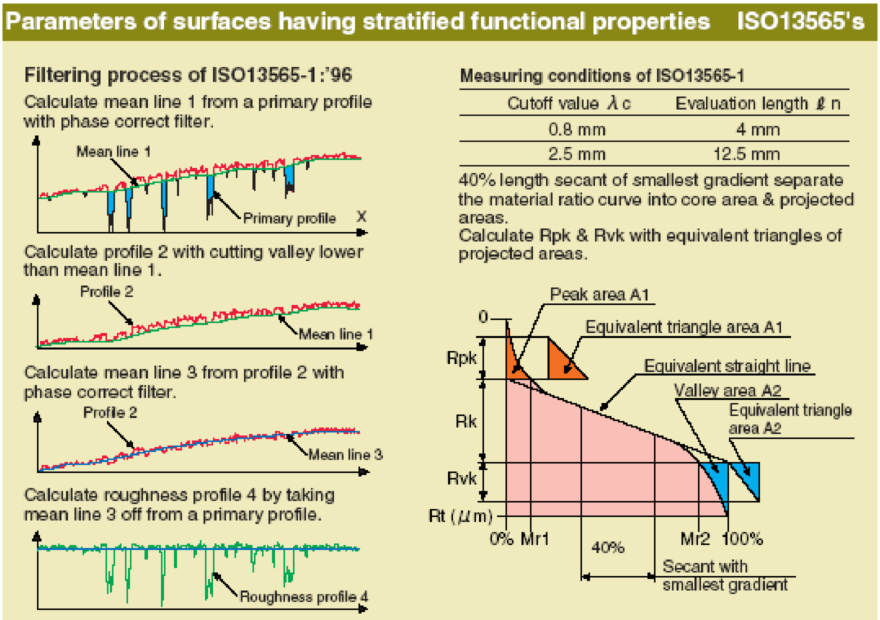


Figure 3.8. t_p parameter [2].

The filter used to analyze the *bearing ratio parameters* is a Valley Suppression Filter described in ISO 13 565 Part 1 (DIN 4776, see Figure 3.9 below).


Parameters of surfaces having stratified functional properties ISO13565's

Filtering process of ISO13565-1:'96

Calculate mean line 1 from a primary profile with phase correct filter.

Calculate profile 2 with cutting valley lower than mean line 1.

Calculate mean line 3 from profile 2 with phase correct filter.

Calculate roughness profile 4 by taking mean line 3 off from a primary profile.

Measuring conditions of ISO13565-1

Cutoff value λc	Evaluation length ℓn
0.8 mm	4 mm
2.5 mm	12.5 mm

40% length secant of smallest gradient separate the material ratio curve into core area & projected areas.
Calculate Rpk & Rvk with equivalent triangles of projected areas.

Figure 3.9. Filtering process and Bearing Ratio Parameters, [12].

Kernal roughness depth or core roughness depth, R_k

R_k is the long term running surface which will influence the performance and life of the cylinder. Also it is the depth of the *roughness core profile* or the load bearing area of the surface.

Reduced peak height, R_{pk}

R_{pk} is a measurement of the peaks of the surface in the cylinder bore. These peaks will be the areas of most rapid wear when the engine is first run.

Reduced valley depth, R_{vk}

R_{vk} is a measurement of the oil retaining capability of the valleys of the surface produced during the machining process (plateau honing).

Bearing ratio at peak to core transition, R_{mr1} or Mr1

Mr1 is the Material Ratio corresponding to the upper limit position of the roughness core (where the R_{pk} and R_k depths meet on the material ratio curve).

Bearing ratio at core to valley transition, R_{mr2} or Mr2

Mr2 is the Material Ratio corresponding to the lower limit position of the roughness core (where the R_{vk} and R_k depths meet on the material ratio curve).

Oil retention "volume", A_2 or V_o or reduced valley volume, R_{vo}

A_2 is the 'valley area' of the material ratio curve. It is calculated as the area of a right angled triangle of base length *Mr2* to 100% and height R_{vk}. The "area" of the valleys in the R_k construction is denoted by A_2. It is related to R_{vk} and *Mr2*:

$$A_2 = \frac{1}{2}\frac{R_{vk}(100\% - Mr2)}{100\%} \qquad [\mu\text{m}] \qquad (3.9)$$

S_k Family parameters, S_k, S_{pk}, S_{vk}, S_{mr1} and S_{mr2}

These parameters are 3D equivalents of the following 2D parameters: R_k, R_{pk}, R_{vk}, R_{mr1}, and R_{mr2}. They are called: *linear area material ratio curve parameters* or the *S_k family parameters* (see the Figure 3.10), i.e. they are an extension from 2D to 3D according to ISO 13565-2: 1996.

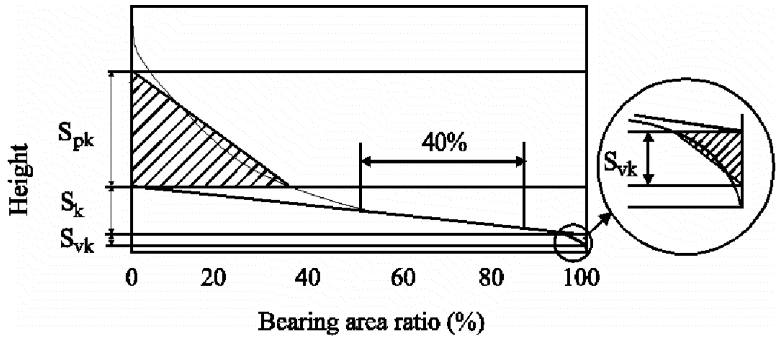


Figure 3.10. S_k Family parameters.

Valley void volume of the surface, SV2 or Vvv

SV2 is a 3D equivalent of the 2D parameter R_{vo} (A_2). It is derived from the volume information of areal material ratio curves. It is defined as a void volume in the valley zone from 80% to 100% surface material ratio:

$$Vvv = \frac{Vv(h_{0.8})}{(M-1)(N-1)\cdot \Delta x \cdot \Delta y} \qquad [\mathrm{mm}^3] \qquad (3.10)$$

Where $Vv(h_{0.8})$ is determined as:

$$\begin{aligned}
Vv(h_{0.8}) = \frac{\Delta x \cdot \Delta y}{9} \Bigg\{ & 16\sum_{j=1}^{\frac{N}{2}-1}\sum_{i=1}^{\frac{M}{2}-1}\left(h_{0.8} - \eta(x_{2i}, y_{2j})\right) + 8\left[\sum_{j=1}^{\frac{N}{2}-1}\sum_{i=2}^{\frac{M}{2}-1}\left(h_{0.8} - \eta(x_{2i-1}, y_{2j})\right) + \sum_{j=1}^{\frac{N}{2}-1}\sum_{i=2}^{\frac{M}{2}-1}\left(h_{0.8} - \eta(x_{2i}, y_{2j-1})\right)\right] + \\
& + 4\left[\sum_{j=2}^{\frac{N}{2}-1}\sum_{i=2}^{\frac{M}{2}-1}\left(h_{0.8} - \eta(x_{2i-1}, y_{2j-1})\right) + \sum_{i=1}^{\frac{M}{2}-1}\left(h_{0.8} - \left(\eta(x_{2i}, y_1) + \eta(x_{2i}, y_{n-1})\right)\right) + \sum_{j=1}^{\frac{N}{2}-1}\left(h_{0.8} - \left(\eta(x_1, y_{2j}) + \eta(x_{m-1}, y_{sj})\right)\right)\right] + \\
& + 2\left[\sum_{i=2}^{\frac{M}{2}-1}\left(h_{0.8} - \left(\eta(x_{2i-1}, y_1) + \eta(x_{2i-1}, y_{n-1})\right)\right) + \sum_{j=1}^{\frac{N}{2}-1}\left(h_{0.8} - \left(\eta(x_1, y_{2j-1}) + \eta(x_{m-1}, y_{sj-1})\right)\right)\right] + \\
& + \left[h_{0.8} - \left(\eta(x_1, y_1) + \eta(x_1, y_{n-1}) + \eta(x_{m-1}, y_1) + \eta(x_{m-1}, y_{n-1})\right)\right]\Bigg\},\ \eta(x,y) \le h_{0.8} \qquad (3.11)
\end{aligned}$$

3.3 Measurement techniques and instruments

There are two types of measurement techniques and instruments used in this thesis work. It is the tactile Stylus method and the Interference method. On the Stylus are performed 2D and 3D measurements, and on the Interferometer 3D measurements.

3.3.1 Stylus

A typical surface measuring instrument consists of a stylus with a small tip (fingernail), a gauge or transducer, a traverse datum and a processor. The surface is measured by moving the stylus across the surface (see Figure 3.11). As the stylus moves up and down along the surface, the transducer converts this movement into a signal which is then exported to a processor which converts this into a number and usually a visual profile. For correct data collection, the gauge needs to pass over the surface in a straight line such that only the stylus tip follows the surface under test. This is done using a straightness datum. This can consist of some form of datum bar that is usually lapped or precision ground to a high straightness tolerance. On small portable instruments this is not always a good option and can add to the expense of the instrument. In these cases, it is possible to use an alternative means of datum. This is a skid.

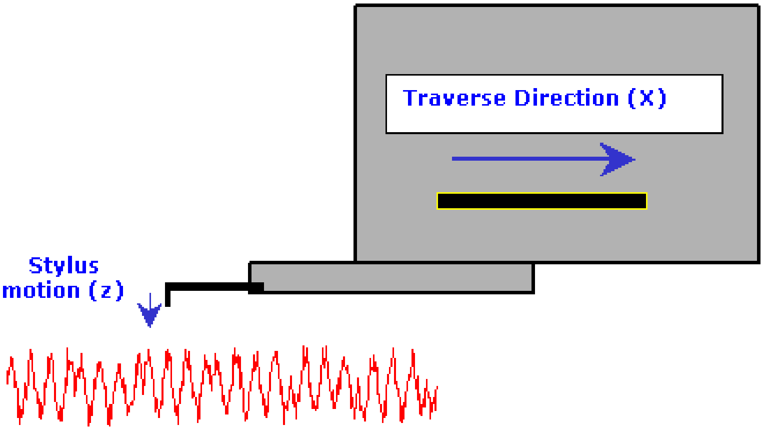


Figure 3.11. Schema of how the stylus works [10].

3.3.2 Interferometer

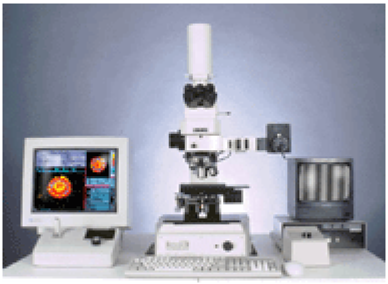


Figure 3.12. The Phase-Shift Interferometer used in Toponova.

An optical method of assessing surface features of an area uses the principle of interference of light. The method is briefly this: when light rays are reflected between two surfaces which are not parallel, the different path lengths at various parts of the surface cause phase changes in the light reflected back to the observer. Consequently, some rays cancel whereas some augment each other, giving rise to a pattern of alternate dark and light fringes. Their spacing and shape depend on reflector and on the regularity of the surface.

The texture irregularities are reproduced as irregularities in the interference pattern and, under adapted viewing conditions, the displacement of the fringes is a measure of the roughness size.

4 Experiments

This chapter presents the experimental part of the project, mainly carried out in the lab of Toponova AB. It is divided into two sections. Section 4.1 introduces the first step of the characterization of the Cylinder Liner Surface by Roughness Parameters Analysis. It is measuring and determining of how many measurements are needed for the parameter stability sake. Section 4.2 describes the second step of the project. Here samples of different Cylinder Liner Types are measured, some standardized roughness parameters are computed and together with the Profile data are exported from the measuring software.

4.1 Determination of the needed number of measurements

The starting step of the characterization of the Cylinder Liner Surface by Roughness Parameters Analysis is to measure and determine how many measurements are needed.

For that purpose a sample of a Cylinder Liner of a Volvo Truck engine is measured on a SOMICRONIC Stylus and on the MicroXAM 100 HR Interferometer in the Toponova's lab. On the stylus are performed 2D and 3D measurements and on the interferometer 3D measurements with magnification of 10X and 50X. The measurement conditions are given in the Tables 4.1 and 4.2. The measurement data are analyzed on the measuring software-SURFASCAN and computed the standardized parameters (see the Table 4.3). These parameters are exported from the measuring software and converted into MATLAB files for an Analysis of a needed number of measurements.

The needed number of measurements is determined using the *converging means theory*, which is appropriate when control a small series even a single work-piece [11]. The stability (convergence) of various parameters is checked computing all combinations of the mean- ${}_nM_i$ for $i=2, 3,\dots, n-1;$ where n is total checked number of measurements.

For example for $n=5$ measurements, the mean combinations' vectors ${}_5M_i$ are calculated by the formulas 4.1, 4.2 and 4.3:

$$
\begin{aligned}
{}_5M_2=[&(x_1+x_2)\quad (x_1+x_3)\quad (x_1+x_4)\quad (x_1+x_5)\quad (x_2+x_3)\quad (x_2+x_4)\ldots\\
&(x_2+x_5)\quad (x_3+x_4)\quad (x_3+x_5)\quad (x_4+x_5)]/2
\end{aligned}
\tag{4.1}
$$

$$
\begin{aligned}
{}_5M_3=[&(x_1+x_2+x_3)\ (x_1+x_2+x_4)\ (x_1+x_2+x_5)\ (x_1+x_3+x_4)\ (x_1+x_3+x_5)\ldots\\
&(x_1+x_4+x_5)\ (x_2+x_3+x_4)\ (x_2+x_3+x_5)\ (x_2+x_4+x_5)\ (x_3+x_4+x_5)]/3
\end{aligned}
\tag{4.2}
$$

$$
\begin{aligned}
{}_5M_4=[&(x_1+x_2+x_3+x_4)\quad (x_1+x_2+x_3+x_5)\quad (x_1+x_3+x_4+x_5)\ldots\\
&(x_2+x_3+x_4+x_5)]/4
\end{aligned}
\tag{4.3}
$$

where: x_1, x_2, x_3, x_4 and x_5 are the measured values of the considered parameter.

With plotting: all measured values of the considered parameter versus the first measurement; all mean combinations of any two measured values (${}_nM_2$) versus the second measurement; all mean combinations of any three measured values (${}_nM_3$) versus the third measurement; and so on up to the mean of n measured values for the nth measurement, it can be seen from the Figure 4.1 that they converge from the 1st to the nth (9th) measurement.

Then, the *Dispersion Range*, *DR,* is calculated for $i=2, 3, \ldots, n-1$ of number of measurements respectively, using the following formula:

$$
DR(i)=max|(m-[max({}_nM_i)\quad min({}_nM_i)])/m*100| \quad [\%] \tag{4.4}
$$

m is the mean value of the considered parameter of n total checked number of measurements.

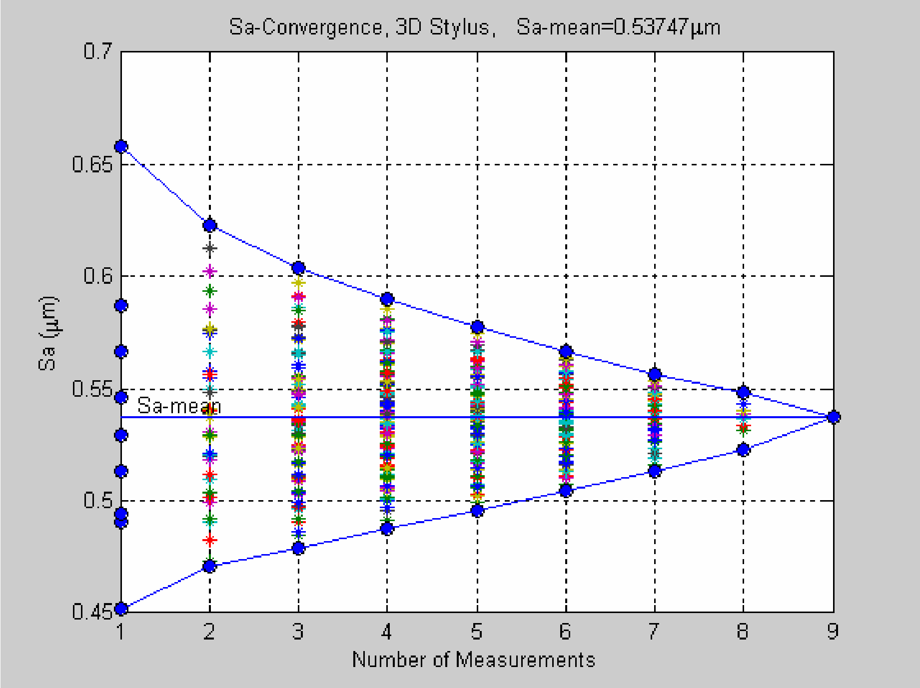


Figure 4.1. Convergence of the Sa parameter for n=9 number of 3D measurements on a Stylus instrument.

The *dispersion range* values are calculated, and checked if they are less than 20% [9], for all the parameters of all kinds of measurements. The calculation of *the dispersion range* is done in MATLAB, and the name of the created MATLAB script is *conver.m* (see Appendix A).

For the most of the parameters it is found that it is enough to make five measurements in order to have a stable parameter's mean value.

It is decided to make five 2D and 3D measurements per sample on the Stylus instrument and nine 3D measurements per sample on the interferometer. The greater number of optical measurements (the nine 3D measurements) is due to the larger dispersion in the parameter's mean value on the one hand, and the relatively short measuring time needed on the other.

4.2 Measurements and Computation of the Standardized Parameters

Once determined the number of the measurements it is ready to take the real measurements. From Volvo trucks are given six types of cylinder liners, marked as type A, B, C, D, E and F. Three samples of each type are taken, which makes eighteen samples. So it makes 180 2D and 3D Stylus measurements and 324 3D optical measurements that give totally 504 measurements.

The next is to choose the measurement conditions. On the following two tables below are given the chosen *measurement conditions* for the *Stylus* and the *Interferometer* (see Table 4.1 and Table 4.2 respectively).

Table 4.1. Measurement conditions on Stylus Instrument.

Somicronic Stylus Instrument (Stylus tip radius (r=2µm))		
	2D Measurements	*3D* Measurements
Number of measures per sample	5	5
Measurement length/ area	12.5 mm; cut-off 2.5 mm	2*2 mm^2; cut-off 0.8 mm
Sampling distance	x=1 µm	x=y=15 µm
Form Filtering	Polynomial of the 4th order	B-spline
Roughness Filtering	13565 Valley Suppression	Gauss and Double Gauss

Table 4.2. Measurement conditions on Interferometer.

MicroXAM 100 HR -Interferometer (*3D* Measurements)		
	Magnification *10X*	Magnification *50X*
Number of measures per sample	9	9
Measuring area	808.12*613.96 µm	161.94*123.04 µm
Sampling distance	1.1*1.3 µm	0.55*0.55 µm
Filtering	Tilt & Cylinder Form Removal	Tilt & Cylinder Form Removal

After all the measurements are done, the 2D and 3D parameters are computed on the measuring software SURFASCAN. The profiles of the 2D stylus measurements are filtered and exported from SURFASCAN for the next step-Groove parameters analysis.

In the Table 4.3 below is given an overview of all 2D and 3D parameters computed in the software SURFASCAN for both the stylus and the interference measurements. The Table 4.3 contains other parameters which are not included in the Quality Control Method described in the GOETZE Honing Guide [1]. Those parameters will be used for a further study to examine the relation among them.

The values of the 2D parameters, stylus measurements are given in the Table B1 and Table B2, Appendix B. The values of the 3D parameters, stylus measurements are given in the Table B3 and Table B4, Appendix B. The values of the 3D parameters, interferometer measurements, magnification 10X, are given in the Table B5, Table B6 and Table B7, Appendix B. The values of the 3D parameters, interferometer measurements, magnification 50X, are given in the Table B8, Table B9 and Table B10, Appendix B.

Table 4.3. 2D and 3D parameters computed in the software Surfascan.

Type	***2D***	***3D***
Amplitude Parameters	Average roughness, R_a	Average roughness, S_a
	Total peak-to-valley Height, R_t	Total peak to valley height, S_t
	Total waviness height, W_t	
	Average peak to valley roughness, Rz_{DIN}	
Spacing Parameters	High spot count, R_{hsc}	Density of summits, S_{ds}
	Valley count, R_{vc}	
Bearing Ratio Parameters	Bearing ratio percentage, t_{pa}	
	Core roughness depth, R_k	Core roughness depth, S_k
	Reduced peak height, R_{pk}	Reduced peak height, S_{pk}
	Reduced valley depth, R_{vk}	Reduced valley depth, S_{vk}
	Bearing ratio at peak to core transition, R_{mr1}	Peak material component, S_{mr1}
	Bearing ratio at core to valley transition, R_{mr2}	Valley material component, S_{mr2}
	Reduced valley volume, R_{vo} (A_2)	Valley void volume, $SV2$ (Vvv)

5 Grading Analysis

This Chapter presents the post-experimental part, i.e. the part of analyses of the project. It is divided into three sections. Section 5.1 describes the third step: Groove Parameters Analysis. The MATLAB script *groove.m* is created to extract and compute the Groove Parameters. Section 5.2 deals with an Analysis of the Grading Factors of the GOETZE defined parameters. It is the fourth step and it is not worked out in detail because of the time constraint. Only the idea of the procedure is presented. Finally, the Section 5.3 presents the last step. It is the Determination of the Final Grade and because it depends on the Parameter Grading Factors (the previous step); the principle of its procedure is described.

5.1 Groove Parameters Analysis

Five 2D parameters are needed to be computed to characterize the cylinder liner topography [3]. Two of them are the standardized parameters: t_{pa} (*percentage bearing ratio*) at depth of 1 µm and 5% reference and W_t (*macrowaviness*). They were computed in the measuring software SURFASCAN. The other three parameters are the Groove parameters, and they are computed in MATLAB. Prior to the computation of these groove parameters, the profile data were exported from the measuring software SURFASCAN and converted into MATLAB m-files.

The three groove parameters are: *the groove width*, *the groove height* and *the distance between grooves*.

Preliminary in the computation of these parameters, each valley that reaches or crosses c_2=-1 µm is considered as a groove, where c_2 is the lower threshold (the line two on the Figure 5.1.).

Groove width, *a*

The groove width for the *i*-th groove is determined at the upper threshold c_1 (line 1 on the Figure 5.1). The upper threshold c_1 is determined as a height from the mean (zero) line where the number of the peaks is close to 20% of the maximum number of peaks. This implies that the maximum number of peaks is found first. Doing this, some adjacent valleys can have the same width points. Those valleys are corrected and joined together representing one groove. For example, the *i*th groove (see Figure 5.1) is consisted of three adjacent valleys that cross the lower threshold c_2.

a is a mean value:

$$a = \frac{1}{n}\sum_{i=1}^{n} a_i \qquad \text{[mm]} \qquad (5.1)$$

where: *n* is the concerned number of grooves.

Groove height, *C*

The groove height of the *i*th groove c_i is determined as a height from the groove bottom point up to the mean value of the two top groove points. So *C* is a mean value of the concerned profile grooves:

$$C = \frac{1}{n}\sum_{i=1}^{n} c_i \qquad [\mu\text{m}] \qquad (5.2)$$

Distance between grooves, *d*

The Distance between grooves *d* is the average distance between the bottom groove points.

The calculation of the *groove parameters* is done using the created MATLAB script: *groove.m* (see Appendix A). The values of the *groove parameters* are given together with the standardized 2D parameters in the Appendix B (Table B1 and Table B2).

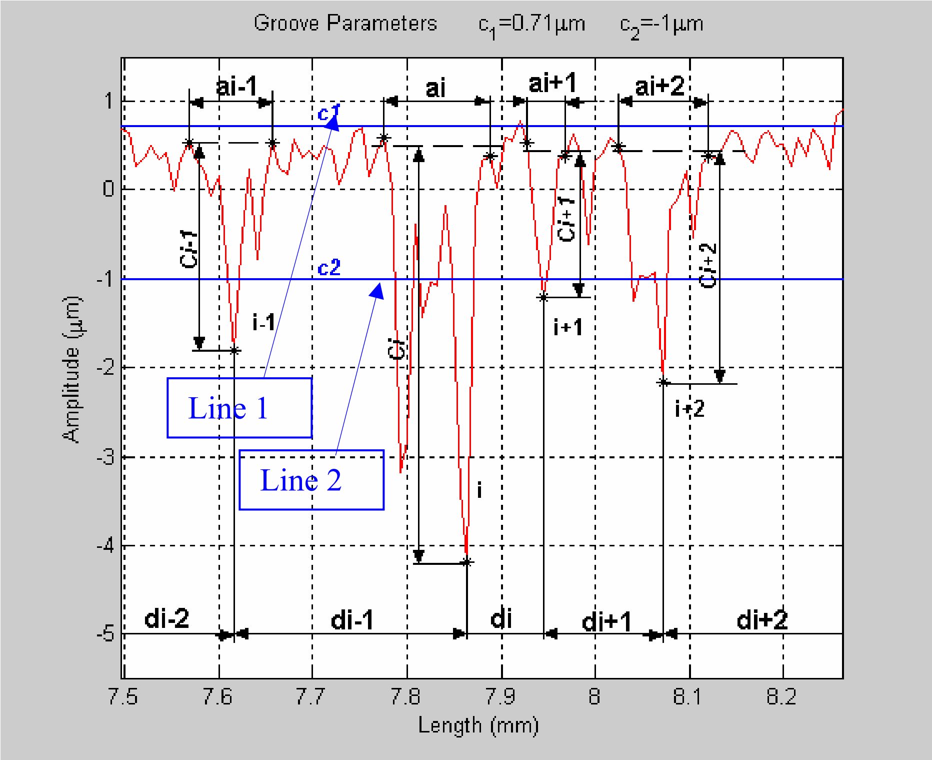


Figure 5.1. The groove parameters: a (groove width), c (groove height) and d (distance between the grooves).

5.2 Grading Factor Analysis

The idea behind the foundation of the *parameter grading criteria* lies on the principles of the *statistical process control*. For a determination of the *control limits* of a certain parameter the *X control chart* method [13] can be used. This can be easily done using the built-in function *xbarplot* in MATLAB.

Because this method requires measuring and analyzing at least 25 samples per Cylinder Liner Type the lack of time does not allow that. Instead the general idea in creating a diagram for determining the *grading factor* of an arbitrary *parameter* is presented.

For instance, if it is to create a diagram for determining the *grading factor* of the *d* -parameter of the Cylinder Liner Type A, it can be seen from the values of the parameter that they are normally distributed with a **Mean** and standard deviation **sigma** (see Figure 5.2). Using the MATLAB function *xbarplot*, the Lower Control Limit (LCL), and the Upper Control Limit (UCL) can be computed. It is usually to define three unacceptable (1, 2, and 3 in Figure 5.2) and three acceptable (4, 5 and 6 in Figure 5.2) *grading factors*. The a*cceptable grading factors* are found as heights of the rectangles obtained by dividing the area between LCL and UCL in *five* equal rectangular areas. The *unacceptable grading factors* are found as heights of the rectangles obtained by dividing the area between **-3 sigma** and LCL in *tree* equal rectangular areas and as many again in the area between UCL and**+3 sigma**. So the best *grading factor* is found as a height of the rectangle centered in the Mean of the population of this *parameter*.

The creation of the diagrams of the *grading factors* of the other parameters is in the same way.

The *grading factors* indicate which parameter can be improved in order to achieve a better overall *grade*.

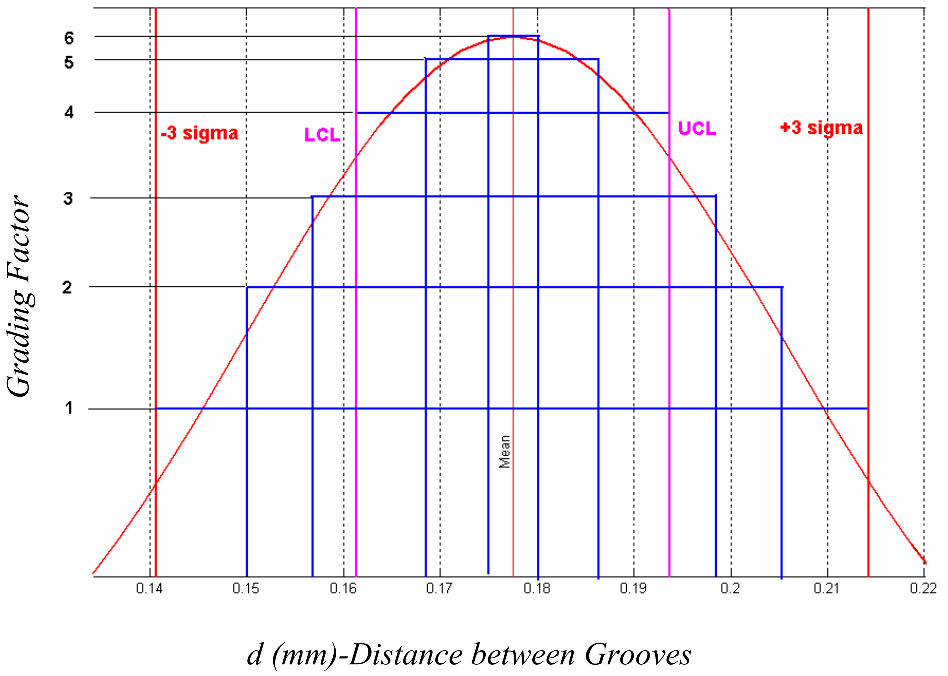


Figure 5.2. Diagram for determining the Grading Factor of the ***d****-Parameter.*

5.3 Determination of the Final Grade

The last step of the characterization of the *cylinder liner topography* is a determination of the final grade and it is given in general. In the Table 5.1 is given an overview of the procedure of the determination of the final grade [3].

This Procedure is as follows:

- For a computed Quantity of a *(a, C, d, Tpa or Wt)* Parameter from MATLAB, the Grading Factor is found from the corresponding Grading Factor Diagram (Figure 5.2);
- The multiplication of each Grading Factor by its Weight gives five Parameter Grades;
- The sum of the Parameter Grades (*1, 2, 3, 4* and *5*) rounded up or down results in Interim Grade (IG) of that *profile measurement*; and

- The lower IG among the *profile measurements* is the Final Grade (FG).

Table 5.1. An overview of the Determination of the Final Grade.

Parameter	**Weight**	**Cylinder Liner Running Surface**					
		Profile 1			**Profile 2**		
		Quantity	**Grading Factor**	**Grade**	**Quantity**	**Grading Factor**	**Grade**
Groove width, *a* [mm]	0.15			Param. Grade 1			Param. Grade 1
Groove height, *C* [µm]	0.15			Param. Grade 2			Param. Grade 2
Distance between grooves, *d* [mm]	0.10			Param. Grade 3			Param. Grade 3
Percentage Bearing ratio t_{pa} at 1µm [%]	0.45			Param. Grade 4			Param. Grade 4
Macro waviness, W_t [µm]	0.15			Param. Grade 5			Param. Grade 5
Sum				$\sum$			$\sum$
Interim Grade, IG				IG 1			IG 2
Final Grade, FG							FG

6 Conclusions and Discussions

Characterization of a Cylinder Liner Surface by Roughness Parameters Analysis automating the method described in the GOETZE Honing Guide [1] is subject of this thesis work. It can be done in five steps.

The first step represents the determination of the needed number of measurements per sample. A sample of a Cylinder Liner from a Volvo Truck engine was measured on a Stylus and on an Interferometer. The standardized Roughness Parameters were computed in the measuring software SURFASCAN. The MATLAB script *conver.m* was created to compute the Dispersion Range of these parameters. With checking if the Dispersion Range for all the parameters is within the tolerance limits it was found that five 2D and 3D for the Stylus and nine 3D measurements for the Interferometer were needed.

In the second step, three samples of each six different Cylinder Liner Types were measured on a Stylus (2D and 3D measurements) and on an Interferometer (3D measurements). The standardized 2D and 3D parameters were computed in the measuring software SURFASCAN and exported together with the Profile Data. The values of these parameters are enclosed in the Appendix B. Two 2D parameters (t_{pa} at -1 µm and 5% reference and W_t-Macrowaviness) are to be used for a realization of the next steps of this project. The rest of the parameters are to be used for getting a better orientation and assessment when all steps of the characterization are to be fully completed and also for a further study in another project to study the relation among them.

In the third step the Profile Data were converted into MATLAB m-files and the MATLAB script *groove.m* was created to extract and compute the Groove Parameters. The values of these parameters are given in the Appendix B.

The fourth step: ‘Grading Factor Analysis’ was not worked out in detail because 25 (or more) samples per Cylinder Liner Type were to be measured and the time constraint did not allow that. This drawback would not have been existed if a statistician was consulted in the beginning of the project. However, the general idea in creating the diagram for determining the Grading Factor of the *d* (Distance between Grooves) parameter was presented.

The final step is the Determination of the Final Grade. Because it depends on the Parameter Grading Factors (the previous step), only the general idea of its procedure is described.

Another drawback is the use of two software packages (SURFASCAN and MATLAB), which makes this method to take longer time than it should be. This can be a challenge for the companies which make surface roughness software packages to improve the program and reduce the computation time with unique software.

The benefits of this thesis work are the created MATLAB scripts: *conver.m* and *groove.m* which can be used in the automation of the Quality Control Method for a quick and an objective inspection in the production of the Cylinder Liners.

7 References

1. GOETZE AG Honing Guide, (1988), *Rating Criteria For The Honing of Cylinder Runing Surfaces*, Burscheid, Hauptverwaltung, D-5093.
2. Precision Devices Inc., (2005), *Surface Metrology Guide* www.predev.com/smg, Milan, MI 48160, USA.
3. Ludolf Herbst, Mike Heglin, Tony Hoult and Horst Lindner, (2004), *Targeting Diesel Engine Efficiency*, Industrial Laser Solutions, http://ils.pennnet.com/Articles/Article_Display.cfm?Section=Archives&Subsection=Display&ARTICLE_ID=214247&KEYWORD=Targeting%20diesle .
4. Mark C. Malburg, (2002), *Cylinder Bore Surface Texture Analysis*, Digital Metrology Solutions Inc, ASME B46.1 Michigan, USA, http://www.digitalmetrology.com/Papers/CylinderBoreNoBkgd.pdf .
5. Tom Thomas, (1999), *Rough surfaces*, London: Imperial College Press, 278 ISBN 1-86094-100-1.
6. Stout K.J., (1994), *Three-dimensional surface topography; measurement, interpretation and applications*, p.89-121, London and Briston Pennsylvania: Penton Press, ISBN 1-85718-004-6.
7. J. Beyerer, D. Krahe, and F. Puente Leon, (2001), *Characterization of Cylinder Bores*: Metrology and properties of engineered surfaces, p. 243-p. 248, Boston/Dordrecht/London: Kluwer Academic Publishers, ISBN 0-412-80640-1.
8. E. Mainsah and D. T. Ndumi, (2001), *Surface Characterization using neural networks:* Metrology and properties of engineered surfaces, p. 283-p. 303, Boston/Dordrecht/London: Kluwer Academic Publishers, ISBN 0-412-80640-1.
9. Robert Ohlsson, Bengt Göran Rosen and John Westberg, (2003),*The Interrelationship of 3D Surface Characterization Techniques with Standardized 2D Techniques*: Advanced Techniques for Assessment Surface Topography: Development of a Basis for 3D Surface Texture Standards 'Surfstand', p. 197-p. 215, London, Kogan Page Science, ISBN 1-903996-11-2.

10. Taylor Hobson Ltd, *The Layman's Guide to Surface Texture*, http://www.taylor-hobson.com/faqsurfacedetail.asp?faqid=20, Leicester, England

11. E.Lardon and F. Lopez, (2002), *Optimization of Roughness 3D Parameters Measurements*, p.31, Master Thesis, Halmstad Högskola.

12. Tokyo Seimitsu Co., LTD, *Explanation of Surface Characteristics and Standards,* http://www.accretech.jp/products-en/measuring/sfcm30a, Tokyo, Japan

13. Douglas C. Montgomery, George C. Runger and Norma Faris Hubele, (2004), *Engineering Statistics',* p. 400-404, John Wiley & Sons, Inc., USA.

8 Appendices

8.1 Appendix A: Matlab scripts

conver.m

```
% The program conver.m, calculates the Dispersion Range and plots the
% Convergence of the Mean values of the given parameter values.
% It is based on the Convergence Means Theory.

load d3_10;            % Load the parameter data from the parameters matrix
s=d3_10(1:9,11);       % Make n-element vector of the parameter values
s=sort(s);

n=length(s);                              % Number of measurements
s1=s(1);  s9=mean(s); m=mean(s);                        % The first & last
%measurement
plot(1,s,'ko','MarkerFaceColor','b'); hold on;         % Plot the Parameter
%Values vs the 1st measurement

%--------------------------------------------------------------------------------
% FOR LOOP for calculating the Dispersion Range from the 2nd to the (n-
%1)th measurement

for i=2:n-1
   si=nchoosek(1:n,i);           % Combinations of the i-th measurement
   S=sum(s(si)')/i;                        % Mean of the i-th measurement
   Smin(i)=min(S); Smax(i)=max(S); % Min & Max of the i-th
%measurement
```

```
   DR=[Smax(i) Smin(i)];
   dr(i)=max(abs((m-(DR))/m*100)); % Dispersion Range of the i-th
%measurement
   plot(i,S,'*'); hold on;                 % Plot the i-th Mean Combination
%points vs the i-th measurement
end


format bank;
D_Ra=dr(2:length(dr))      % The Dispersion Range Vector from the 2nd to
%the (n-1)th measurement


% Plot the Mean Line and the Convergence Points & Lines with a blue
%color


Smin(1)=min(s); Smin(n)=m;
Smax(1)=max(s); Smax(n)=m;
ezplot(m,[1,n]); hold on; grid on;
plot(Smin,'ko','MarkerFaceColor','b'); hold on; plot(Smin,'-b');
hold on; plot(Smax,'ko','MarkerFaceColor','b'); hold on; plot(Smax,'-b');
xlabel('Number of Measurements'); ylabel('Sk (\mum)');
title(['Sk-Convergence, 3D Interferometer 10X, Sk-
mean=',num2str(m),'\mum']);
text(1.2,m+0.005,'Sk-mean');
```

groove.m

```
% The program, groove.m, calculates the Groove Parameters: a-Width, C-
%Height and d-Distance between Grooves and plots their locations on the
%profile


load s3_5;                    %Load the profile data
 pro=s3_5; x=pro(:,1); y=pro(:,2);        % x-Profile Length (mm) and y-
%Profile Amplitude (um)


c1prcnt=0.2;              % Percent (20%) of  number of peaks  out of the c1-
%threshold
prcofc1=0.5; % Percent of min Height (the lower limit) from which the
%Groove Width-a is %determined
ypmax=max(y);            % Maximum height


%-----------------------------------------------------------------------
% Determination of the upper c1-threshold, i.e. no of peaks
%-----------------------------------------------------------------------


p1=[]; vvv=0; height=[]; C=0;      %Pre-defined quantities


for bb=0.1:0.01:ypmax  %Height FOR LOOP to find max no of peaks and
%corresponding c1 height
y1p=find(y>bb);
C=C+1;                %Counter
if length(y1p)~=1          %IF (SINGLES) LOOP for checking if multiple
%peaks exist
```

```
%-------------------------------------------------------------------------------------
%Separate single peaks
y2p=[]; y3p=[];

for i=2:length(y1p)
   dif2=y1p(i)-y1p(i-1);
   if dif2==1
      y2p=[y2p y1p(i-1)]; y3p=[y3p y1p(i)];
      y4p=union(y2p,y3p);
   end
end
y1sp=setdiff(y1p,y4p); %y1 -singles

%-------------------------------------------------------------------------------------
%Separate multiple peaks and find the full vector of the successive
%multiples
nrp=0;h1p=[];
  for i=2:length(y4p)
     y4lfp=y4p(i-1); y4rp=y4p(i);
      if y4rp==y4lfp+1
         nrp=[nrp y4lfp y4rp];
      else
         nrp=0;
      end
    n2p=nrp(2:length(nrp)); n2p=unique(n2p);
     if isempty(n2p)
        h1p=[h1p i-1];        %finds the full vector of successive multiples
     end
```

```
end
h1p=[h1p length(y4p)];      %Add the multiples vector after i-1, i.e. after the
%last multiples vector


y1gp=[y1sp,h1p];
ngp=length(y1gp);


else %if only singles exist


y1gp=y1p;                 %y1-GROOVES: Indices of the grooves
ngp=length(y1gp);           %Number of Grooves
end                     %ends the checking IF (SINGLES) LOOP


if ngp==1
   break                   %Discard the heights with only one peak
end


vvv=[vvv ngp];
difngp=diff(vvv);
if difngp(C)==0
   ngp=[]; bb=[];              %Discard the (unnecessary) data with the same
%number of peaks
end
p1=[p1 ngp];
height=[height bb];


end                     %ends final Height FOR LOOP
```

```
[npmax,npmxindx]=max(p1);   %Maximum number of peaks & The Index
%of the Maximum number of peaks


np=c1prcnt*npmax;           %The Number of considered peaks np: is 20%
%of the peaks outside the c1-treshold


npindcs=find(p1>=np); npindx=npindcs(length(npindcs));
c100=height(npmxindx);              %c1-for 100%, i.e max no of peaks
npeaks=p1(npindx);              %The Real Number of considered peaks

%------------------------------------------------------------------------------------
c1=height(npindx);         %c1-(upper)-treshold
%------------------------------------------------------------------------------------
c1perc=(p1/npmax*100); pp=[height' c1perc' p1'];

%-----------------------------------------------------------------------
% Determination of the Grooves
%-----------------------------------------------------------------------


ymn=min(y);                        % Minimum depth
CC=find(y>prcofc1*c1); % Find & Consider the Grooves with a full Width
%at the profile beginning % and end
y=y(CC(1):CC(end)); x=x(CC(1):CC(end));


%-----------------------------------------------------------------------
c2=-1;              % c2-threshold is -1 (um)
%-----------------------------------------------------------------------


y1=find(y<c2);
```

```
if length(y1)~=1 %IF (SINGLES) LOOP for checking if multiples exist

%-----------------------------------------------------------------------------------
%Separate singles
y2=[]; y3=[];
for i=2:length(y1)
    dif1=y1(i)-y1(i-1);
    if dif1==1
        y2=[y2 y1(i-1)]; y3=[y3 y1(i)];
        y4=union(y2,y3);
    end
end
y1s=setdiff(y1,y4); %y1 -singles

%-----------------------------------------------------------------------------------
%Separate multiples
 nr=0; h1=[];
   for i=2:length(y4)
      y4lf=y4(i-1); y4r=y4(i);
        if y4r==y4lf+1
            nr=[nr y4lf y4r];
        else
            nr=0;
        end
     n2=nr(2:length(nr)); n2=unique(n2);
      if isempty(n2)
          h1=[h1 i-1]; %finds the full vector of successive multiples
```

```
      end
end
h1=[h1 length(y4)]; %Add the multiples vector after i-1, i.e. after the last
%multiples vector


%------------------------------------------------------------------------
%Find min of multiples
nr=0; ym=[];
   for i=2:length(y4)
      y4lf=y4(i-1); y4r=y4(i);
        if y4r==y4lf+1
            nr=[nr y4lf y4r];
        else
            nr=0;
        end
     n2=nr(2:length(nr)); n2=unique(n2);
     for j=1:length(h1)
        if i==h1(j)
        yg=min(y(n2));
        ym=[ym;yg];
        end
     end
end
[ygm,ia,ib]=intersect(ym,y); y1g=union(y1s',ib); ng=length(y1g);

else                    %if only singles exist


y1g=y1;                 %y1-GROOVES: Indices of the grooves
```

```
ng=length(y1g);        %Number of Grooves

end                    %ends the checking IF (SINGLES) LOOP



%------------------------------------------------------------------------------------
%a-width-PARAMETER
%------------------------------------------------------------------------------------

ar=[]; al=[];               % Pre-defined index of the right and left Groove
%Width point

for i=1:length(y1g)                % FOR LOOP for General Groove width
%determination
   ygr=(y1g(i)+1); h=1;
     while  y(ygr)<prcofc1*c1   % Left Width Point
        h=h+1; ygr=y1g(i)+h;
    end
ar=[ar ygr];

    yglf=(y1g(i)-1); g=1;
     while  y(yglf)<prcofc1*c1  % Right Width Point
        g=g+1; yglf=y1g(i)-g;
    end
al=[al yglf];
end

difal=diff(al);
```

```
ia=0; iia=[];
for i=2:length(al)              % FOR LOOP for finding of adjacent grooves
%with the same width
   difal=al(i)-al(i-1);
   if difal==0
         ia=[ia i-1 i]; iia=[iia i-1 i];
       else
          ia=0;
       end
    nial=ia(2:length(ia)); nial=unique(nial);
    A(i)={[nial]};
       if ~isempty(nial) & length(A{i})>length(A{i-1})
          A(i-1)={[]};
       end
   end
end
iia=unique(iia);
yy1g=[];
for i=1:length(A)
yy1g=[yy1g min(y(y1g(A{i})))];  % Find min of those adjacent grooves
%and make them 1 groove
end
[yygm,iaa,ib]=intersect(yy1g,y); ib=sort(ib); y1gdef=setdiff(y1g(iia),ib);


Y1g=setdiff(y1g,y1gdef);
Ng=length(Y1g);             % Corrected (Reduced) Number of Grooves due
%to the joining
```

```
al=unique(al); ar=unique(ar); a=x(ar)-x(al); am=mean(a);

%------------------------------------------------------------------------------------
% C-Groove Height
%------------------------------------------------------------------------------------

C=(y(ar)+y(al))/2+abs(y(Y1g)); Cm=mean(C);

%------------------------------------------------------------------------------------
%d-Distance between Grooves
%------------------------------------------------------------------------------------

d=diff(x(Y1g)); dm=sum(d)/Ng;

% Plotting of the profile, c1 & c2-thresholds, the bottom groove point (*),
% and the left & right width ponts (*)

plot(x,y,'r'); hold on; grid on; ezplot(c2,[2.4,15.1]); hold on;
plot(x(Y1g),y(Y1g),'k*');hold on;
ezplot(c1,[2.4,15.1]); hold on; plot(x(al),y(al),'k*'); hold on;
plot(x(ar),y(ar),'k*');
xlabel('Length (mm)'); ylabel('Amplitude (\mum)'); axis([2.4 15.1 ymn
max(y)+0.5]);
title(['Groove Parameters c_1=',num2str(c1),'\mum
c_2=',num2str(c2),'\mum']);
```

8.2 Appendix B: Parameter Tables

Table B1. 2D Parameters, stylus measurements.

Sample	Groove Parameters			tpa	Wt	Ra	Rt	RzDIN	Rpk	Rk	Rvk	Rmr1	Rmr2	tpa	Rvo	Rhsc	Rvc
	a	d	C	%	µm	µm	µm	µm	µm	µm	µm	%	%	%	µm		
	mm	mm	µm	1µm5%										2µm 5%		at 0.3 µm	at-3 µm
A1	0.0581	0.1613	2.6	74.8	0.16	0.60	6.44	5.03	0.10	0.85	1.71	3.20	69.10	92.2	0.26	235	10
	0.0492	0.1497	2.5	76.1	0.15	0.58	6.11	4.69	0.08	0.83	1.65	2.62	69.44	93.1	0.25	260	9
	0.0519	0.1563	2.5	75.0	0.18	0.60	6.95	5.18	0.08	0.74	1.79	3.46	67.37	92.0	0.29	240	10
	0.0556	0.1684	2.6	76.4	0.17	0.57	6.44	5.31	0.11	0.73	1.69	3.65	67.65	92.8	0.27	249	9
	0.0560	0.1961	2.6	76.5	0.14	0.56	6.71	4.77	0.10	0.74	1.61	3.13	67.01	93.5	0.27	241	10
A2	0.0559	0.1553	2.6	69.8	0.16	0.61	5.67	4.75	0.11	1.02	1.59	3.26	69.99	91.2	0.24	249	11
	0.0533	0.1603	2.4	72.1	0.13	0.59	6.24	4.63	0.18	0.95	1.65	2.88	70.76	91.4	0.24	251	6
	0.0626	0.1596	2.4	71.8	0.19	0.58	4.46	4.16	0.13	1.01	1.60	3.07	72.68	91.3	0.22	248	7
	0.0588	0.1559	2.5	71.1	0.20	0.62	6.42	4.79	0.15	1.00	1.62	2.37	69.25	91.2	0.25	243	9
	0.0563	0.1449	2.5	69.5	0.14	0.63	5.52	4.73	0.10	1.08	1.61	2.30	70.33	91.4	0.24	252	12
A3	0.0554	0.2131	2.2	85.4	0.16	0.44	7.53	4.72	0.10	0.57	1.58	4.16	73.96	95.9	0.21	281	5
	0.0584	0.2239	2.7	84.7	0.16	0.47	8.00	5.80	0.09	0.52	1.68	4.73	72.30	94.9	0.23	276	12
	0.0510	0.2064	2.3	83.9	0.10	0.45	6.57	4.65	0.09	0.56	1.62	3.78	73.83	95.0	0.21	285	6
	0.0523	0.1980	2.4	84.5	0.15	0.46	5.78	5.01	0.07	0.56	1.60	3.20	72.12	94.6	0.22	284	7
	0.0548	0.2135	2.1	86.2	0.09	0.39	5.55	3.87	0.09	0.52	1.35	4.80	73.83	96.5	0.18	285	4
B1	0.0564	0.1609	2.7	72.8	0.20	0.71	8.27	5.87	0.09	0.56	2.18	2.88	60.36	89.3	0.43	181	14
	0.0540	0.1485	2.8	72.5	0.28	0.73	6.57	5.54	0.18	0.54	2.36	4.73	63.24	89.0	0.43	172	18
	0.0588	0.1657	2.8	74.6	0.23	0.73	6.29	5.44	0.06	0.46	2.41	4.03	62.38	89.5	0.45	156	21
	0.0567	0.1822	2.8	76.3	0.24	0.68	6.67	5.59	0.12	0.44	2.33	5.69	64.58	90.1	0.41	160	17
	0.0617	0.1852	2.7	75.8	0.18	0.64	8.52	5.69	0.09	0.45	2.18	5.63	65.26	90.5	0.38	165	15
B2	0.0571	0.1575	2.9	71.9	0.25	0.83	9.79	6.94	0.11	0.51	2.68	4.16	61.23	86.6	0.52	164	17
	0.0576	0.1614	2.8	72.5	0.28	0.75	9.13	5.99	0.14	0.64	2.36	3.52	64.04	87.1	0.42	173	16
	0.0575	0.1479	2.9	72.6	0.23	0.81	6.09	5.51	0.06	0.49	2.57	3.71	59.89	86.6	0.52	158	16
	0.0541	0.1526	2.8	73.0	0.32	0.75	7.75	5.42	0.12	0.49	2.42	5.57	62.38	88.2	0.46	166	18
	0.0557	0.1555	2.7	72.7	0.20	0.73	5.95	4.49	0.09	0.42	2.39	5.12	60.87	88.4	0.47	161	13
B3	0.0486	0.1884	2.8	82.1	0.15	0.56	5.17	4.37	0.12	0.36	2.03	5.44	67.63	93.1	0.33	187	10
	0.0488	0.1957	2.5	83.3	0.15	0.53	5.51	4.71	0.07	0.30	1.99	6.01	68.59	93.7	0.31	182	11
	0.0518	0.1713	2.5	81.1	0.15	0.57	5.74	5.09	0.07	0.34	2.08	5.50	67.07	93.3	0.34	164	13
	0.0478	0.1715	2.5	80.7	0.22	0.58	5.43	4.74	0.06	0.38	2.08	4.80	67.31	92.3	0.34	182	12
	0.0529	0.1743	2.5	80.8	0.14	0.60	5.50	4.66	0.07	0.38	2.17	5.44	67.75	91.8	0.35	165	10
C1	0.0537	0.2522	2.2	87.4	0.13	0.41	6.90	4.80	0.08	0.32	1.59	7.42	71.80	95.3	0.22	247	8
	0.0503	0.2144	2.3	87.9	0.10	0.41	5.51	4.30	0.12	0.31	1.64	5.31	72.11	96.0	0.23	254	7
	0.0477	0.1947	2.4	86.9	0.21	0.43	8.46	5.51	0.10	0.33	1.76	5.82	73.13	95.6	0.24	264	10
	0.0537	0.2522	2.2	91.0	0.11	0.34	6.78	4.26	0.07	0.30	1.46	6.33	75.38	97.0	0.18	156	4
	0.0513	0.2309	2.2	88.4	0.16	0.39	4.63	4.06	0.08	0.31	1.57	6.53	73.51	96.2	0.21	231	7
C2	0.0562	0.2505	2.3	89.0	0.10	0.37	9.14	5.15	0.07	0.29	1.55	6.65	74.86	96.9	0.20	205	7
	0.0538	0.2357	2.3	89.1	0.13	0.38	5.76	4.44	0.10	0.33	1.59	6.78	75.13	96.7	0.20	223	7
	0.0560	0.2416	2.2	88.9	0.12	0.40	5.40	4.21	0.10	0.34	1.61	7.55	73.45	96.5	0.21	267	3
	0.0587	0.2465	2.3	88.5	0.19	0.38	8.28	4.17	0.11	0.33	1.58	7.48	75.32	96.7	0.20	220	3
	0.0585	0.2366	2.3	89.8	0.12	0.38	7.68	4.74	0.11	0.33	1.57	7.93	74.73	96.5	0.20	216	6
C3	0.0500	0.2276	2.3	89.9	0.11	0.37	8.06	4.87	0.08	0.29	1.63	6.33	76.33	96.6	0.19	193	8
	0.0551	0.2565	2.1	90.5	0.11	0.33	4.07	3.40	0.10	0.30	1.43	5.88	76.60	97.1	0.17	132	4
	0.0513	0.2224	2.0	89.4	0.15	0.35	4.19	3.47	0.08	0.30	1.48	6.78	74.81	97.3	0.19	189	3
	0.0562	0.2675	2.3	88.9	0.13	0.37	5.38	4.21	0.13	0.29	1.57	8.13	74.92	96.4	0.20	196	7
	0.0566	0.2185	2.2	89.0	0.17	0.36	5.72	3.88	0.09	0.29	1.43	8.57	72.87	96.6	0.19	184	4

Table B2. 2D Parameters, stylus measurements.

Sample	Groove Parameters			tpa	Wt	Ra	Rt	RzDIN	Rpk	Rk	Rvk	Rmr1	Rmr2	tpa	Rvo	Rhsc	Rvc
	a	d	C	%	µm	µm	µm	µm	µm	µm	µm	%	%	%	µm		
	mm	mm	µm	1µm5%										2µm 5%		at 0.3 µm	at-3 µm
D1	0.0625	0.2286	2.5	83.7	0.18	0.52	6.55	4.34	0.09	0.36	1.92	6.01	68.93	93.7	0.30	217	8
	0.0631	0.2414	2.7	83.2	0.11	0.53	7.78	4.85	0.09	0.36	2.10	4.86	71.15	93.4	0.30	194	7
	0.0553	0.2112	2.5	84.7	0.17	0.53	9.04	5.65	0.08	0.34	1.95	6.33	68.99	93.9	0.30	205	8
	0.0657	0.2623	2.4	85.7	0.15	0.45	5.36	4.36	0.09	0.34	1.77	6.21	71.59	94.5	0.25	248	9
	0.0609	0.2224	2.6	83.1	0.16	0.53	5.74	4.60	0.08	0.34	2.08	5.50	70.38	92.8	0.31	204	10
D2	0.0573	0.2170	2.2	86.3	0.13	0.43	5.82	4.21	0.07	0.28	1.68	7.81	70.83	95.8	0.24	249	7
	0.0553	0.2478	2.3	86.2	0.13	0.46	5.89	4.21	0.07	0.29	1.80	5.12	71.21	94.8	0.26	264	6
	0.0570	0.2107	2.4	85.2	0.10	0.48	5.18	4.17	0.10	0.30	1.81	6.91	68.97	95.0	0.28	219	8
	0.0622	0.2394	2.2	86.4	0.19	0.45	5.33	4.20	0.09	0.33	1.78	5.50	72.00	95.3	0.25	235	5
	0.0588	0.2240	2.5	85.5	0.20	0.48	6.90	4.25	0.08	0.32	1.88	7.29	71.42	94.6	0.27	229	7
D3	0.0548	0.2146	2.5	85.4	0.17	0.52	9.13	5.35	0.10	0.34	2.13	6.65	72.36	94.5	0.29	230	9
	0.0608	0.2924	2.7	86.8	0.18	0.47	9.39	5.21	0.08	0.32	1.93	7.23	73.26	94.5	0.26	278	9
	0.0665	0.2850	2.5	87.6	0.16	0.45	8.13	5.30	0.09	0.33	1.88	6.91	73.77	95.6	0.25	267	10
	0.0684	0.2726	2.4	86.9	0.14	0.46	8.00	5.42	0.12	0.34	1.80	7.29	72.04	95.8	0.25	236	5
	0.0633	0.2483	2.2	86.2	0.21	0.40	7.10	4.43	0.11	0.33	1.63	7.03	73.53	95.3	0.22	232	5
E1	0.0496	0.2784	1.9	90.3	0.09	0.31	3.88	3.07	0.06	0.20	1.31	6.52	73.85	98.0	0.17	41	2
	0.0511	0.2796	1.9	90.3	0.13	0.29	6.48	3.47	0.05	0.19	1.25	7.49	73.90	97.3	0.16	31	1
	0.0449	0.2632	2.1	90.9	0.11	0.36	12.79	5.39	0.05	0.20	1.48	6.20	72.95	97.6	0.20	112	4
	0.0443	0.2546	2.0	92.5	0.09	0.32	4.90	3.56	0.04	0.20	1.39	6.33	73.96	97.9	0.18	54	4
	0.0436	0.2140	2.0	88.7	0.11	0.37	6.43	3.80	0.06	0.21	1.58	8.19	72.94	96.9	0.21	141	3
E2	0.0463	0.2575	2.1	89.2	0.19	0.35	4.37	3.44	0.08	0.24	1.46	5.63	73.77	96.8	0.19	144	3
	0.0488	0.3141	2.1	89.5	0.14	0.31	4.69	3.28	0.07	0.20	1.33	7.80	74.30	97.4	0.17	55	2
	0.0468	0.2320	2.1	88.9	0.09	0.39	5.60	3.71	0.06	0.22	1.52	6.01	69.50	97.0	0.23	236	3
	0.0498	0.2443	2.2	89.4	0.11	0.39	5.84	4.10	0.06	0.23	1.53	5.82	70.89	97.4	0.22	203	4
	0.0472	0.3255	2.1	92.2	0.14	0.29	4.89	3.47	0.06	0.18	1.35	7.93	76.73	98.2	0.16	20	4
E3	0.0476	0.2049	2.0	89.7	0.08	0.38	5.05	3.80	0.07	0.19	1.53	7.67	70.91	97.0	0.22	165	2
	0.0482	0.2724	2.0	91.1	0.12	0.31	4.19	3.54	0.06	0.19	1.49	7.16	76.85	97.2	0.17	38	5
	0.0471	0.2789	1.9	91.8	0.10	0.31	6.79	3.55	0.05	0.17	1.37	6.53	74.54	98.0	0.17	19	1
	0.0432	0.2328	1.8	91.6	0.11	0.32	3.78	2.89	0.06	0.18	1.34	6.65	72.94	98.0	0.18	48	1
	0.0487	0.3216	1.8	92.7	0.10	0.25	3.46	2.82	0.05	0.17	1.16	6.97	76.46	98.2	0.14	5	2
F1	0.1029	0.2737	2.5	86.5	0.27	0.38	8.34	4.68	0.12	0.51	1.51	5.44	77.80	95.7	0.17	152	6
	0.1118	0.2996	2.7	85.1	0.28	0.45	5.47	4.77	0.11	0.58	1.78	4.99	76.58	94.4	0.21	144	12
	0.0831	0.2482	3.0	85.8	0.27	0.49	11.03	6.75	0.09	0.52	1.91	4.09	74.36	94.4	0.25	163	15
	0.1040	0.2696	3.0	86.0	0.27	0.48	8.96	6.29	0.13	0.55	1.91	6.01	75.64	94.3	0.23	161	15
	0.1083	0.2667	2.9	85.8	0.36	0.48	7.50	6.03	0.19	0.62	1.97	6.91	77.81	94.2	0.22	170	12
F2	0.1062	0.2703	2.5	87.4	0.14	0.38	6.17	4.54	0.11	0.53	1.45	5.95	76.66	95.4	0.17	160	7
	0.1059	0.3126	2.9	87.4	0.22	0.44	7.68	5.86	0.09	0.54	1.72	5.82	76.02	95.3	0.21	158	11
	0.1019	0.3099	2.7	87.9	0.17	0.39	7.86	5.10	0.09	0.56	1.58	5.24	78.13	95.2	0.17	140	8
	0.0867	0.2709	3.1	87.4	0.43	0.53	18.10	7.24	0.15	0.57	2.38	6.14	78.52	95.3	0.26	167	13
	0.1070	0.3474	3.2	87.6	0.24	0.46	9.66	6.47	0.13	0.57	1.86	5.12	77.03	95.2	0.21	165	14
F3	0.0875	0.2548	3.3	85.2	0.32	0.56	9.98	7.59	0.12	0.54	2.36	5.82	75.58	93.3	0.29	159	14
	0.0778	0.2352	2.9	86.3	0.25	0.54	8.91	6.25	0.14	0.59	2.17	4.67	75.24	93.3	0.27	170	12
	0.0934	0.2474	2.8	85.7	0.32	0.47	8.08	5.58	0.13	0.56	1.85	6.07	76.09	94.3	0.22	147	12
	0.0970	0.3155	3.2	85.3	0.31	0.52	7.97	6.64	0.11	0.55	2.27	5.95	77.03	93.2	0.26	179	17
	0.0870	0.2937	3.3	86.0	0.28	0.54	10.26	6.94	0.15	0.59	2.17	5.50	75.38	94.1	0.27	162	15

Table B3. 3D Parameters, stylus measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm^2	µm	µm	µm	%	%	mm^3
A1	9.672	0.5	439.06	0.93	0.07	1.558	3.97235	74.8	0.000796
	11.93	0.5	449.55	0.93	0.04	1.682	4.02105	76.2	0.000812
	10.73	0.5	420.58	0.9	0.07	1.632	4.34259	73	0.000895
	8.483	0.6	423.58	1.01	0.05	1.708	3.4136	72.9	0.00094
	11.99	0.5	459.04	0.78	0.04	1.806	3.30239	70.7	0.001076
A2	11.8	0.5	434.07	1.29	0.07	1.546	3.56934	79	0.000659
	9.883	0.6	454.3	1.05	0.04	1.919	3.14263	72.9	0.001058
	11.81	0.5	442.81	1.08	0.09	1.687	3.93254	75.6	0.000836
	9.948	0.7	408.34	1.08	0.14	2.06	4.14982	72.3	0.001161
	11.37	0.6	442.06	1.12	0.09	1.913	4.18475	74.6	0.000988
A3	7.013	0.3	433.57	0.66	0.11	1.252	7.22415	78.2	0.000553
	8.445	0.5	426.07	1.18	0.12	1.558	5.33057	79.7	0.000643
	11.4	0.5	447.3	0.85	0.06	2.139	3.73916	75.6	0.001062
	10.3	0.5	447.05	0.77	0.06	1.896	5.24514	76.9	0.000889
	10.6	0.4	445.55	0.69	0.07	1.774	5.54698	77.9	0.000795
B1	8.203	0.7	326.92	0.94	0.1	2.217	4.92643	69.6	0.001371
	8.88	0.7	341.16	0.74	0.06	2.171	4.32002	66.6	0.001471
	7.034	0.6	354.4	0.79	0.06	1.814	4.23963	69.3	0.001132
	7.776	0.6	352.9	0.56	0.05	1.963	4.15526	66.4	0.001339
	8.633	0.6	358.64	0.72	0.03	2.334	5.75906	73.1	0.001274
B2	13.47	0.6	360.14	1.12	0.14	2.052	7.13804	77.9	0.000922
	9.754	0.8	360.39	0.73	0.02	2.818	3.03694	67.4	0.001867
	11.08	0.7	362.64	0.68	0.03	2.676	3.64749	66.7	0.001813
	7.812	0.6	374.88	0.75	0.12	2.035	4.11033	67.3	0.001353
	10.36	0.6	370.13	0.67	0.13	2.28	5.18315	69.8	0.0014
B3	8.857	0.4	381.12	0.44	0.05	1.723	5.60912	72.2	0.000972
	6.846	0.5	367.63	0.57	0.04	1.684	4.39731	70.4	0.001014
	6.395	0.3	412.09	0.4	0.06	1.464	5.54116	79.4	0.000612
	6.44	0.5	363.89	0.45	0.04	2.012	4.52451	70.7	0.001199
	10.82	0.4	376.87	0.49	0.03	1.76	4.51518	72.7	0.000976
C1	4.653	0.2	409.09	0.44	0.11	0.992	6.42354	79.5	0.000414
	3.938	0.2	446.8	0.26	0.06	0.803	7.51429	81.1	0.000308
	13.51	0.3	430.07	0.37	0.03	1.438	7.63208	80	0.000583
	5.471	0.3	423.58	0.3	0.04	1.159	6.05087	75.3	0.000582
	5.338	0.3	427.07	0.35	0.05	1.144	6.77322	77.8	0.000516
C2	10.43	0.2	443.81	0.32	0.06	1.057	6.78907	80.5	0.000419
	8.121	0.2	442.56	0.36	0.05	1.086	7.26831	77.2	0.000503
	8.174	0.2	434.07	0.32	0.06	1.211	7.27543	80.3	0.000484
	5.88	0.3	432.32	0.37	0.06	1.181	6.47084	79	0.000504
	4.507	0.2	419.08	0.33	0.06	1.138	6.74378	78.8	0.00049
C3	6.461	0.2	455.79	0.42	0.08	1.182	7.29289	82.4	0.000421
	6.311	0.3	418.08	0.53	0.07	1.342	5.62695	79.7	0.000552
	8.457	0.2	446.3	0.37	0.11	1.121	10.2467	82.1	0.000407
	15.04	0.2	440.31	0.32	0.07	1.302	6.63842	79.5	0.000542
	4.744	0.2	431.57	0.3	0.04	1.187	6.81065	80.4	0.000473

Table B4. 3D Parameters, stylus measurements.

Sample	St	Sa	Sds	Ssc	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	/µm	µm	µm	µm	%	%	mm³
D1	5.871	0.4	354.9	0.00173	0.44	0.05	1.58	6.55643	76.3	0.000762
	7.11	0.4	350.9	0.00232	0.44	0.05	1.72	5.10191	72.4	0.000964
	5.856	0.3	349.65	0.00199	0.49	0.07	1.496	8.75428	79.8	0.000614
	10.85	0.3	350.4	0.00186	0.48	0.03	1.598	5.59644	79.4	0.000668
	5.764	0.4	350.65	0.00187	0.47	0.04	1.638	4.8655	76.7	0.000776
D2	10.28	0.3	375.12	0.00199	0.38	0.03	1.616	6.05065	75.5	0.000803
	7.901	0.3	360.64	0.00234	0.43	0.08	1.52	6.67748	76	0.000742
	7.258	0.3	373.63	0.00196	0.41	0.15	1.454	10.5678	79.4	0.000607
	7.987	0.4	364.39	0.00216	0.38	0.08	1.576	5.70381	73.9	0.000834
	9.401	0.3	357.89	0.00185	0.43	0.04	1.568	6.05111	76.5	0.000748
D3	6.642	0.3	367.63	0.00183	0.31	0.05	1.363	6.43006	76.6	0.000648
	9.432	0.2	369.13	0.00164	0.36	0.05	1.408	9.23184	83	0.000486
	13.14	0.4	347.4	0.00238	0.66	0.05	2.011	11.1486	80.8	0.000786
	6.974	0.4	354.9	0.00182	0.45	0.06	1.666	7.167	78.4	0.000732
	9.487	0.4	352.15	0.00207	0.53	0.06	1.993	7.13309	79	0.000848
E1	5.983	0.2	448.55	0.001	0.23	0.03	1.149	7.38027	83.5	0.000386
	5.283	0.2	446.05	0.00098	0.29	0.05	1.261	10.5337	86.4	0.000347
	5.291	0.3	418.83	0.00154	0.45	0.12	1.438	10.5016	81.7	0.000534
	20.42	0.3	422.33	0.00145	0.34	0.07	1.85	8.21974	79.3	0.000779
	14.08	0.2	434.07	0.00148	0.29	0.1	1.259	7.37106	77.5	0.000575
E2	4.872	0.2	440.31	0.0013	0.24	0.08	0.908	9.46064	79.3	0.000382
	6.661	0.3	427.57	0.00159	0.37	0.06	1.468	6.27975	77.4	0.000674
	5.915	0.3	440.56	0.0018	0.44	0.05	1.413	4.18359	78.4	0.000621
	6.965	0.2	445.8	0.0013	0.28	0.09	1.2	10.8599	81.8	0.000445
	7.492	0.3	420.33	0.00173	0.31	0.07	1.463	7.44415	74.7	0.000752
E3	4.985	0.2	409.59	0.00135	0.41	0.08	1.142	7.7204	84.5	0.000358
	13.36	0.3	397.35	0.00149	0.38	0.03	1.561	9.11684	81.5	0.000587
	7.418	0.2	424.58	0.00122	0.3	0.06	1.416	8.30219	82.1	0.000514
	7.336	0.4	426.07	0.00174	0.44	0.03	1.728	7.51314	78.4	0.000759
	6.455	0.2	414.09	0.00143	0.36	0.04	1.18	6.30674	80.1	0.000477
F1	14.54	0.5	285.46	0.00174	1.1	0.37	2.17	11.0219	83.9	0.000709
	8.566	0.3	316.93	0.00149	0.65	0.27	1.622	9.88652	83.5	0.000545
	15.73	0.5	296.45	0.00198	0.86	0.08	2.172	6.89276	79	0.000929
	12.81	0.2	342.66	0.00163	0.56	0.04	1.085	6.72391	83.1	0.000373
	11.53	0.4	337.91	0.00175	0.58	0.06	1.695	5.31795	77.4	0.000778
F2	8.939	0.3	312.44	0.00178	0.64	0.06	1.515	7.1188	81.7	0.000562
	11.5	0.3	322.68	0.00171	0.7	0.06	1.406	5.89116	81.6	0.000526
	14.81	0.3	314.19	0.00166	0.63	0.05	1.708	6.89259	81.3	0.00065
	12.73	0.3	333.42	0.00159	0.49	0.06	1.336	7.71809	81	0.000517
	13.82	0.3	319.93	0.00163	0.63	0.03	1.415	6.21411	79.9	0.000579
F3	9.346	0.4	308.44	0.00171	0.64	0.02	1.499	5.77192	78.9	0.000644
	13.02	0.4	317.93	0.00189	0.64	0.07	1.743	6.98126	79.3	0.000731
	18.4	0.4	305.94	0.00172	0.6	0.04	1.977	6.16854	77.7	0.000896
	12.56	0.6	302.95	0.00201	0.87	0.14	2.672	6.74827	78.6	0.00116
	18.2	0.3	331.42	0.00167	0.54	0.08	1.613	6.6549	79	0.000688

Table B5. 3D Parameters, 10X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm^2	µm	µm	µm	%	%	mm^3
A1	8.983	0.6	16510	1.13	0.12	1.77	4.21638	74.4	0.000110019
	9.76	0.5	16641	0.98	0.12	1.434	5.55522	78.2	7.57865E-05
	10.08	0.6	14714	1.35	0.16	1.71	4.23597	77.7	9.23102E-05
	8.215	0.5	16788	1.04	0.11	1.504	5.18684	78.8	7.71659E-05
	8.262	0.6	15867	1.23	0.11	1.792	4.24148	77	9.97149E-05
	17.7	0.8	14553	1.27	0.18	3.129	6.87762	77.6	0.000169933
	7.244	0.6	15134	1.32	0.14	1.575	4.13479	79.7	7.7591E-05
	7.935	0.7	15378	1.44	0.2	2.266	6.46444	77.3	0.00012445
	10.71	0.4	15730	0.94	0.25	1.409	6.77255	82.4	6.02852E-05
A2	8.294	0.7	15149	1.37	0.17	2.023	5.1263	76.3	0.000116221
	8.386	0.5	15399	1.01	0.14	1.332	5.3645	76.5	7.59152E-05
	7.834	0.6	16367	1.38	0.2	1.623	5.38004	78.4	8.50604E-05
	9.045	0.5	15666	1.3	0.14	1.358	4.95411	79.8	6.65956E-05
	6.188	0.5	14511	1.44	0.2	1.24	5.00886	81.5	5.56438E-05
	12.8	0.5	16477	1.12	0.13	1.416	6.01783	80.2	6.80392E-05
	6.328	0.6	15413	1.51	0.15	1.41	3.87131	78.3	7.4302E-05
	9.336	0.6	15229	1.39	0.13	1.327	4.1697	78.8	6.81433E-05
	8.632	0.6	16245	1.09	0.15	1.838	5.2402	76.6	0.00010409
A3	6.331	0.4	16995	1.13	0.15	1.047	5.48036	82.7	4.39231E-05
	6.026	0.5	18174	1.06	0.18	1.403	6.2872	79.2	7.08314E-05
	6.587	0.5	17934	0.99	0.15	1.605	6.19062	81.5	7.21138E-05
	7.383	0.5	17520	1.03	0.13	1.688	5.31611	77.6	9.15139E-05
	6.642	0.3	18853	0.76	0.14	0.808	8.11706	85.7	2.79192E-05
	7.801	0.5	18934	0.98	0.13	2.141	5.82703	79.4	0.000107154
	9.084	0.4	17160	0.95	0.11	1.207	6.40112	79.7	5.94666E-05
	9.431	0.4	19014	0.86	0.17	1.911	8.15958	82.7	8.00489E-05
	7.67	0.5	17233	1.01	0.14	1.578	5.5388	78.6	8.17513E-05
B1	8.041	0.4	17930	0.66	0.13	1.61	8.07299	78.5	8.40469E-05
	7.599	0.5	17601	0.77	0.17	2.159	7.34161	77.8	0.000116069
	7.436	0.6	20095	1.04	0.18	2	5.18793	75.8	0.000117565
	10.63	0.7	17015	1.3	0.12	1.679	3.30978	71.8	0.000114692
	16.71	0.9	17117	1.19	0.18	3.301	6.10075	74.4	0.000205177
	6.144	0.5	17746	0.87	0.2	1.49	6.73232	73.2	9.67036E-05
	8.212	0.7	18576	0.98	0.17	2.318	6.96462	73.6	0.000148399
	7.21	0.7	17982	1.13	0.17	1.913	4.92973	71.1	0.000134233
	15.3	0.8	17439	1.14	0.19	2.381	5.27145	67.8	0.000185649
B2	8.942	0.7	15958	1.1	0.14	2.291	4.17845	71.8	0.000156441
	7.624	0.7	15844	0.89	0.14	2.233	6.17213	71.8	0.000152931
	11.85	0.9	16974	1.24	0.1	3.722	3.51855	78	0.000198339
	8.19	0.7	16318	1.03	0.16	2.476	5.86942	75.2	0.000148872
	6.812	0.7	16630	0.92	0.14	2.096	4.73192	68.3	0.000160862
	7.271	0.5	18110	0.85	0.13	1.743	5.89487	77.1	9.6718E-05
	8.089	0.8	15999	1.37	0.2	2.202	5.31804	68.2	0.00016961
	10.28	0.8	16591	1.4	0.22	2.297	5.07253	74.5	0.000142127
	7.667	0.6	17537	0.7	0.15	2.432	7.4063	76.6	0.000138096
B3	9.456	0.4	16999	0.62	0.12	1.915	7.82079	78	0.000101998
	11.17	0.5	17754	0.78	0.13	1.806	6.43582	70.8	0.000127647
	6.728	0.4	20943	0.7	0.14	1.902	6.99263	79.5	9.46667E-05
	6.565	0.6	17119	0.81	0.19	2.19	7.25188	75.2	0.000131762
	6.917	0.5	18872	0.69	0.14	2.125	6.49783	77.2	0.000117641
	7.369	0.6	17646	0.8	0.13	2.049	5.34926	70.8	0.000144853
	8.945	0.8	18267	1.05	0.18	2.681	6.81656	69.5	0.000198199
	8.799	0.5	18836	0.76	0.15	2.093	6.18523	74.8	0.000128042
	8.48	0.5	18652	0.71	0.13	1.896	6.21482	72.1	0.000128215

Table B6. 3D Parameters, 10X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	µm	µm	µm	%	%	mm³
C1	7.225	0.4	17870	0.72	0.18	1.815	8.38054	80.4	8.61824E-05
	6.727	0.3	18236	0.59	0.15	1.682	9.2316	84.3	6.39727E-05
	9.126	0.3	18207	0.64	0.13	1.503	8.54528	84.3	5.72109E-05
	7.528	0.5	17266	0.69	0.13	2.357	8.12559	78.1	0.000125239
	9.634	0.5	17622	0.93	0.17	2.217	8.25323	81.9	9.71081E-05
	6.347	0.3	18489	0.69	0.16	1.336	8.47469	82.3	5.73196E-05
	7.257	0.3	17502	0.54	0.14	1.343	9.52851	84.7	4.97061E-05
	8.172	0.4	17603	0.88	0.19	1.675	7.75918	82.7	7.01108E-05
	8.958	0.5	17740	0.75	0.16	1.982	7.4169	79.2	0.000100073
C2	9.687	0.4	18145	0.66	0.17	2.239	9.90072	85.5	7.88759E-05
	12.1	0.5	17785	0.72	0.14	2.7	8.69047	82.9	0.000112044
	5.807	0.3	18137	0.62	0.2	1.23	9.85824	85.9	4.2074E-05
	10.72	0.5	18683	0.68	0.18	2.375	8.84045	81.3	0.000107783
	8.717	0.4	18872	0.77	0.17	1.71	8.66289	82.9	7.08987E-05
	8.721	0.3	19621	0.61	0.16	1.292	9.76995	85.8	4.43827E-05
	6.39	0.3	18354	0.66	0.22	1.576	9.88129	84.2	6.0424E-05
	7.158	0.4	18393	0.68	0.16	2.216	8.59916	83	9.12159E-05
	9.797	0.2	18006	0.55	0.15	1.171	10.4983	87.4	3.57795E-05
C3	5.788	0.2	17011	0.54	0.14	0.94	9.71247	87.1	2.94128E-05
	7.509	0.4	16465	0.66	0.13	2.493	8.62023	84.7	9.22102E-05
	6.281	0.5	16831	0.7	0.19	2.018	8.51974	78.5	0.000105342
	5.077	0.3	17651	0.59	0.15	1.331	9.00985	84.6	4.96161E-05
	5.86	0.4	17535	0.75	0.15	1.79	7.6368	82.5	7.61525E-05
	5.57	0.3	17553	0.61	0.16	1.205	9.28267	85.3	4.2868E-05
	5.106	0.3	18147	0.65	0.16	1.168	8.40847	82.3	4.99854E-05
	6.006	0.3	16877	0.58	0.14	1.472	8.9741	83.7	5.80489E-05
	9.466	0.4	17682	0.74	0.14	1.831	8.06869	85.3	6.54722E-05
D1	6.261	0.4	17605	0.92	0.17	1.584	7.91628	82.4	6.74896E-05
	7.014	0.4	18309	0.74	0.18	1.836	8.59812	80.1	8.85858E-05
	5.554	0.2	18062	0.54	0.14	1.025	8.87494	84.3	3.913E-05
	6.936	0.4	18590	0.71	0.16	1.757	8.09019	80.2	8.41296E-05
	6.273	0.2	18961	0.49	0.13	0.763	10.9089	88.1	2.20325E-05
	7.068	0.4	18480	0.62	0.15	2.004	8.21658	80.5	9.49198E-05
	7.686	0.4	18582	0.69	0.13	1.653	7.98244	80.8	7.68668E-05
	5.757	0.3	18956	0.58	0.15	1.351	9.52151	85.3	4.81545E-05
	6.89	0.5	17353	0.75	0.15	2.128	7.24457	77.2	0.000117843
D2	7.701	0.5	17127	0.85	0.15	2.109	7.30276	77.6	0.000114306
	7.597	0.3	17187	0.62	0.13	1.502	8.49658	84.4	5.68704E-05
	5.753	0.4	17855	0.65	0.15	1.762	8.20162	80.2	8.45358E-05
	4.982	0.3	18187	0.49	0.12	1.498	8.97855	85.6	5.22225E-05
	7.587	0.3	17425	0.64	0.12	1.554	8.08572	82	6.79451E-05
	6.717	0.4	17123	0.82	0.22	1.825	9.62	82.3	7.82708E-05
	6.854	0.6	17270	0.85	0.13	2.114	5.8521	76.2	0.000121833
	5.4	0.4	18859	0.64	0.16	1.579	7.61182	76.8	8.88711E-05
	5.06	0.3	19381	0.53	0.16	1.405	10.1255	85.9	4.81284E-05
D3	9.834	0.7	18681	0.99	0.12	2.63	5.46442	72.5	0.000175494
	11.36	0.5	19821	0.75	0.13	2.057	7.44347	75.8	0.000120633
	7.431	0.5	19883	0.75	0.14	2.342	7.54298	77.9	0.000125553
	5.993	0.4	19915	0.58	0.15	2.152	9.55983	84.6	8.04882E-05
	6.29	0.4	20103	0.61	0.16	2.252	9.04659	81.8	9.94966E-05
	8.22	0.5	20477	0.76	0.14	1.879	6.50596	75.7	0.000110513
	7.965	0.4	19319	0.64	0.14	2.224	8.99144	83.5	8.89471E-05
	6.392	0.4	19629	0.62	0.13	1.494	7.91283	80	7.25682E-05
	7.291	0.5	19474	0.88	0.14	1.641	5.81487	75.1	9.92545E-05

Table B7. 3D Parameters, 10X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	µm	µm	µm	%	%	mm³
E1	8.98	0.2	17727	0.46	0.06	1.293	8.07381	83.1	5.30107E-05
	9.035	0.4	17742	0.53	0.09	1.455	6.40235	76.8	8.19211E-05
	7.263	0.3	18313	0.47	0.11	1.223	8.4545	82.4	5.22282E-05
	7.221	0.3	18408	0.52	0.1	1.551	7.9993	83.2	6.31812E-05
	8.609	0.4	18261	0.65	0.08	2.192	7.13457	86.2	7.35116E-05
	7.643	0.3	17988	0.54	0.09	1.459	6.59211	81.1	6.6965E-05
	4.732	0.2	17671	0.42	0.13	0.877	7.97773	82.4	3.73888E-05
	5.208	0.3	18222	0.48	0.1	1.212	7.45114	81.7	5.37553E-05
	7.12	0.2	17541	0.52	0.12	1.023	7.681	83.3	4.13154E-05
E2	10.69	0.2	17367	0.51	0.1	1.318	7.78391	85	4.79013E-05
	5.705	0.2	17239	0.42	0.14	0.998	8.51501	83.5	4.00256E-05
	5.83	0.2	17514	0.45	0.12	1.101	8.36825	84.8	4.06997E-05
	7.887	0.6	17713	0.75	0.11	2.221	6.2122	75.7	0.000130929
	7.08	0.3	17177	0.56	0.15	1.462	7.57216	79.2	7.36401E-05
	10.97	0.3	17572	0.56	0.12	1.515	7.71966	81.5	6.81169E-05
	6.069	0.3	17338	0.6	0.13	1.393	8.34287	83.9	5.42221E-05
	14.09	0.3	18522	0.53	0.07	1.519	8.12461	81	6.99218E-05
	4.959	0.2	18013	0.43	0.12	0.812	8.04044	83.5	3.24208E-05
E3	7.74	0.5	18458	0.72	0.13	2.041	7.54171	78.4	0.000106916
	8.927	0.3	20037	0.54	0.11	1.468	8.19752	80.3	7.01259E-05
	9.791	0.4	19888	0.61	0.13	1.713	8.07673	80.3	8.19636E-05
	6.889	0.3	17617	0.48	0.12	1.377	8.83476	81.3	6.22746E-05
	8.725	0.3	17386	0.5	0.08	1.617	7.58914	79.9	7.86327E-05
	7.685	0.3	18646	0.5	0.12	1.656	8.02786	81.8	7.30559E-05
	7.702	0.4	18182	0.52	0.11	2.076	8.03296	80.9	9.60146E-05
	5.922	0.2	17177	0.44	0.13	1.09	8.92864	82.6	4.60953E-05
	6.563	0.3	18375	0.48	0.11	1.586	7.29101	82.3	6.80873E-05
F1	7.559	0.4	15339	0.82	0.13	1.407	7.60113	84.2	5.37911E-05
	7.927	0.5	15995	0.92	0.13	1.618	6.70592	79.6	7.9867E-05
	6.721	0.3	16332	0.62	0.13	1.041	8.58546	85.5	3.65927E-05
	7.139	0.4	16639	0.77	0.14	1.675	6.99037	81.2	7.61695E-05
	8.518	0.3	16196	0.64	0.12	1.071	8.30547	85.4	3.79157E-05
	8.281	0.4	15850	0.77	0.12	1.45	6.94263	79.6	7.17006E-05
	7.318	0.4	15641	0.77	0.11	1.437	6.6031	81.3	6.49983E-05
	9.668	0.5	16003	0.94	0.12	2.319	6.30869	81	0.000106726
	10.32	0.6	15521	1.32	0.21	2.48	7.27877	81.2	0.000113248
F2	12.63	0.3	13625	0.67	0.11	1.355	9.00634	86.5	4.4401E-05
	7.206	0.4	14031	0.75	0.12	1.749	6.55476	80.6	8.22097E-05
	9.393	0.4	14149	0.9	0.12	1.789	7.7611	84.9	6.56241E-05
	15.15	0.3	14613	0.69	0.09	1.219	8.48476	85.1	4.3994E-05
	8.891	0.4	13301	0.68	0.12	1.776	7.30258	82.6	7.51101E-05
	12.53	0.4	14681	0.82	0.08	2.01	7.3303	83.8	7.91132E-05
	9.244	0.5	15049	0.91	0.11	2.441	6.71441	82.7	0.000102276
	9.315	0.3	14946	0.67	0.09	1.429	7.92379	83.7	5.66142E-05
	8.613	0.4	15045	0.75	0.1	1.458	6.84066	82.3	6.27149E-05
F3	14.57	0.4	14613	0.84	0.08	2.094	6.59236	81.5	9.40539E-05
	7.443	0.5	15511	0.79	0.11	2.042	6.22791	79.5	0.000101644
	8.794	0.4	16531	0.75	0.11	2.188	7.62754	82.2	9.44707E-05
	7.744	0.4	14629	0.74	0.11	1.612	7.72787	83.6	6.42507E-05
	13.2	0.4	15397	0.81	0.11	2.029	7.92713	83.3	8.2338E-05
	9.348	0.5	15002	0.77	0.09	2.063	6.7115	80.2	9.88355E-05
	13.02	0.5	15128	0.92	0.12	2.239	7.02263	81	0.000103085
	12.48	0.7	15567	1.14	0.11	3.041	6.64832	81.6	0.000135472
	7.908	0.4	15482	0.82	0.16	1.549	8.04416	82.1	6.70684E-05

Table B8. 3D Parameters, 50X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	µm	µm	µm	%	%	mm³
A1	8.124	0.4	323258	1.27	0.38	1.124	4.89111	84.3	1.72631E-06
	5.095	0.6	238414	1.33	0.38	1.386	9.56039	79.9	2.73671E-06
	4.057	0.5	241535	1.07	0.21	0.953	6.6938	74.1	2.42358E-06
	2.72	0.3	331702	0.88	0.16	0.619	4.00488	85.7	8.65022E-07
	4.099	0.5	277919	1.17	0.09	1.023	3.0181	77.3	2.28196E-06
	9.731	0.8	208836	1.81	0.8	2.287	16.5058	85.4	3.284E-06
	5.271	0.6	263795	1.59	0.14	2.36	4.43215	85.6	3.32138E-06
	5.786	0.5	243531	1.39	0.27	1.523	4.97837	83.6	2.45566E-06
	4.041	0.3	228435	0.7	0.25	1.392	11.0073	84.4	2.12821E-06
A2	3.494	0.4	157254	1.19	0.28	0.976	9.12289	85	1.43085E-06
	3.364	0.3	200085	0.76	0.12	0.73	5.50189	78.2	1.55806E-06
	4.193	0.5	222448	1.84	0.26	0.785	7.76451	93.7	4.86845E-07
	2.782	0.3	177569	0.77	0.25	0.521	13.5736	84.7	7.81376E-07
	4.597	0.6	222857	2.15	0.35	0.889	6.72257	87.5	1.08822E-06
	3.47	0.3	207812	0.97	0.21	0.598	5.94373	85	8.81048E-07
	3.733	0.4	169331	1.12	0.14	0.551	4.46693	85.9	7.61963E-07
	4.052	0.3	203667	0.88	0.2	0.701	9.68298	90.3	6.68508E-07
	3.661	0.4	204844	1.41	0.22	0.466	5.44824	88.1	5.44648E-07
A3	5.613	0.5	252793	1.1	0.19	1.6	7.19774	82.5	2.7499E-06
	3.996	0.5	235497	1.31	0.22	1.271	5.98437	81.4	2.3208E-06
	5.374	0.6	215488	1.58	0.05	1.866	1.74987	81.8	3.32863E-06
	4.073	0.4	223983	1.08	0.12	1	5.4681	80.9	1.87391E-06
	2.963	0.2	256171	0.65	0.2	0.652	7.67529	87	8.33892E-07
	2.222	0.2	223062	0.67	0.1	0.325	5.09545	87.9	3.84834E-07
	4.045	0.4	196862	1.29	0.13	1.178	4.20136	88.2	1.35765E-06
	2.847	0.2	246039	0.58	0.14	0.476	7.99288	86.5	6.30598E-07
	3.844	0.3	215386	0.76	0.21	0.896	7.61911	80.9	1.67841E-06
B1	4.485	0.3	225365	0.54	0.63	1.013	13.2794	82.1	1.7812E-06
	5.003	0.5	198908	0.7	0.09	1.834	2.61288	73	4.8523E-06
	5.616	0.3	197015	0.59	0.36	1.361	15.7714	85.3	1.95672E-06
	4.627	0.5	236469	0.86	0.24	1.369	9.57311	71.4	3.84134E-06
	8.448	1.1	248648	4.05	0.32	0.963	4.98347	94.8	4.94599E-07
	3.606	0.3	132589	0.71	0.23	1.099	12.6115	85.9	1.5151E-06
	7.968	0.6	258320	1.99	0.71	0.887	9.41968	89.7	8.93753E-07
	4.583	0.5	218098	1.2	0.27	1.429	9.18841	81.1	2.64494E-06
	6.049	0.6	196350	0.88	0.26	1.997	8.69067	71.7	5.54159E-06
B2	3.813	0.3	204640	0.58	0.21	0.874	12.3705	83.8	1.38645E-06
	4.402	0.6	179360	0.84	0.28	1.752	6.06611	65.8	5.8821E-06
	3.403	0.4	171838	0.94	0.18	0.875	3.87126	77.6	1.92119E-06
	5.559	0.7	162320	0.94	0.06	2.577	3.19803	73.4	6.72894E-06
	5.766	0.5	163906	0.83	0.59	1.357	13.3181	76.3	3.15026E-06
	3.241	0.2	157561	0.48	0.09	0.822	5.29032	83.3	1.34818E-06
	5.288	1.1	232017	2.37	0.17	1.279	1.01054	64.8	4.40963E-06
	5.442	0.6	205459	1.38	0.89	1.592	7.30197	79.6	3.1856E-06
	2.895	0.1	160324	0.32	0.12	0.468	10.6791	88	5.52883E-07
B3	4.195	0.6	178235	1.49	0.1	1.485	2.13889	77.9	3.21861E-06
	5.495	0.6	211395	1.19	0.17	1.354	5.49156	72.4	3.66924E-06
	3.471	0.1	192000	0.31	0.09	0.669	9.1617	85.1	9.78551E-07
	4.867	0.8	165032	0.75	0.07	3.103	4.34995	73	8.22591E-06
	3.069	0.3	188520	0.69	0.4	0.7	20.2624	89.9	6.90532E-07
	4.281	0.6	176239	0.82	0.46	2.07	7.37134	75.1	5.04509E-06
	5.859	0.6	188418	1.12	0.47	1.895	8.03063	77.9	4.11045E-06
	4.933	0.4	156128	0.98	0.26	0.894	5.82458	80.9	1.67365E-06
	3.477	0.4	165032	0.89	0.21	1.085	8.53579	79.9	2.13435E-06

Table B9. 3D Parameters, 50X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	µm	µm	µm	%	%	mm³
C1	5.496	0.6	191130	0.94	0.31	2.604	11.5561	78.2	5.56212E-06
	2.803	0.2	196043	0.47	0.16	0.494	9.66244	86.2	6.66747E-07
	4.683	0.3	208529	0.58	0.16	1.102	7.9468	81.1	2.0439E-06
	7.25	0.7	211241	2.17	0.2	1.267	5.01801	86.1	1.73131E-06
	3.094	0.2	197578	0.48	0.18	0.347	10.3657	88.7	3.84448E-07
	4.532	0.5	210473	0.76	0.12	1.693	5.8704	77.2	3.78356E-06
	3.502	0.3	184222	0.53	0.13	1.137	7.97028	81.8	2.02874E-06
	4.104	0.4	213134	0.97	0.32	1.252	10.8387	81.8	2.23446E-06
	5.524	0.2	214465	0.62	0.25	0.896	8.98308	86.6	1.17512E-06
C2	9.325	0.9	215898	2.16	0.39	2.863	10.0499	84.1	4.47681E-06
	5.72	0.3	178132	0.61	0.29	1.237	16.0709	87.7	1.48905E-06
	3.518	0.1	159812	0.37	0.2	0.44	11.4252	88.3	5.03637E-07
	4.439	0.2	204691	0.48	0.13	0.987	7.05982	84.9	1.46403E-06
	3.926	0.4	176444	0.77	0.2	1.078	7.86824	78.6	2.25975E-06
	3.523	0.2	164981	0.54	0.14	0.467	7.62934	85.7	6.54494E-07
	3.472	0.2	161348	0.6	0.17	0.724	7.19096	84	1.13347E-06
	1.91	0.1	165390	0.37	0.17	0.196	11.0858	90.5	1.82293E-07
	5.94	0.4	180793	0.69	0.14	1.737	5.65197	80.9	3.26038E-06
C3	3.206	0.1	156793	0.4	0.13	0.297	8.88194	90.8	2.6733E-07
	2.556	0.1	150397	0.38	0.14	0.418	9.62768	86.5	5.53475E-07
	3.773	0.3	179923	0.83	0.19	0.83	8.07676	87	1.05691E-06
	3	0.2	166056	0.47	0.14	0.667	9.00064	86.9	8.56404E-07
	3.286	0.3	158533	0.87	0.22	0.621	9.72868	81.3	1.13736E-06
	4.018	0.3	197936	0.67	0.17	1.067	7.69703	82	1.88622E-06
	4.728	0.3	174243	0.56	0.15	1.264	8.23946	84.8	1.88294E-06
	4.798	0.5	169689	1.03	0.14	1.717	5.77511	82.9	2.8767E-06
	2.831	0.2	212827	0.54	0.17	0.437	9.72799	89.8	4.39374E-07
D1	4.01	0.2	166618	0.43	0.14	0.721	11.9628	89.5	7.41064E-07
	3.77	0.4	163650	0.77	0.17	1.662	8.53997	81	3.10119E-06
	2.809	0.2	156589	0.44	0.17	0.468	10.6036	87.8	5.58226E-07
	6.279	0.2	178183	0.52	0.12	0.951	7.72673	85.5	1.3524E-06
	4.363	0.3	180537	0.56	0.13	1.083	8.24853	82.7	1.83385E-06
	5.656	0.2	169996	0.51	0.14	0.816	9.05865	84	1.27904E-06
	4.538	0.5	184375	0.84	0.26	1.343	8.63295	75.4	3.23755E-06
	3.062	0.3	183761	0.71	0.13	0.732	7.78926	83	1.21806E-06
	5.101	0.6	178439	1.51	0.4	1.739	9.88288	80.4	3.34783E-06
D2	4.096	0.3	166056	0.77	0.16	1.504	8.3691	85.2	2.18703E-06
	3.008	0.3	154900	0.76	0.18	1.211	8.62406	85.5	1.71747E-06
	4.448	0.4	177109	0.86	0.19	1.306	6.69523	81.8	2.32543E-06
	4.256	0.4	158738	0.83	0.13	1.629	6.18181	86.3	2.18166E-06
	2.178	0.1	158994	0.4	0.13	0.405	9.25538	85.9	5.58296E-07
	3.712	0.3	168461	0.74	0.26	1.065	9.76827	81.1	1.97741E-06
	6.478	0.4	180896	0.59	0.25	2.315	13.4438	87.2	2.91334E-06
	4.224	0.4	162934	0.88	0.53	1.149	10.7368	82.8	1.94261E-06
	4.706	0.6	187650	0.95	0.46	1.834	11.6091	76.6	4.20442E-06
D3	5.497	0.5	232785	0.8	0.32	2.287	12.9676	81.7	4.09401E-06
	4.206	0.3	212674	0.44	0.38	1.132	13.6373	79.8	2.23904E-06
	5.362	0.6	244452	1.37	0.17	2.124	5.50219	80.5	4.05121E-06
	4.923	0.7	201160	1.37	0.19	1.871	4.24612	72.2	5.10729E-06
	5.926	0.6	200290	1.35	0.16	1.801	3.67193	81.6	3.25589E-06
	4.281	0.2	266047	0.42	0.15	0.799	7.40522	76	1.87587E-06
	4.215	0.3	152648	0.64	0.22	1.489	11.1499	83	2.48562E-06
	2.933	0.2	145689	0.48	0.16	0.712	10.3132	86	9.8027E-07
	5.041	0.3	202183	0.84	0.25	1.039	9.80068	82.2	1.80877E-06

Table B10. 3D Parameters, 50X interferometer measurements.

Sample	St	Sa	Sds	Sk	Spk	Svk	Smr1	Smr2	SV2
	µm	µm	/mm²	µm	µm	µm	%	%	mm³
E1	3.521	0.4	194815	0.78	0.45	0.944	14.3178	80.6	1.7963E-06
	2.068	0.1	199318	0.31	0.12	0.229	13.9673	86.5	3.02503E-07
	4.543	0.3	236213	0.35	0.09	1.136	6.85319	76.8	2.58358E-06
	4.486	0.4	210269	1.07	0.11	1.269	3.51431	83.6	2.04334E-06
	2.194	0.1	190465	0.27	0.09	0.447	6.44311	80	8.74516E-07
	2.942	0.3	175932	0.52	0.06	0.837	4.05327	74.7	2.07485E-06
	3.026	0.1	163036	0.3	0.15	0.523	11.3518	82.3	9.07603E-07
	3.158	0.2	175881	0.41	0.16	0.476	9.59381	84.2	7.37282E-07
	3.351	0.1	172503	0.3	0.08	0.38	5.8902	80.1	7.41081E-07
E2	2.485	0.1	166260	0.32	0.07	0.252	7.00109	86.8	3.2778E-07
	3.573	0.3	214363	0.44	0.07	1.093	5.72842	77	2.46332E-06
	2.783	0.2	184375	0.39	0.16	0.459	8.7187	83	7.66015E-07
	5.015	0.4	213493	0.76	0.23	1.396	11.0403	80.4	2.68865E-06
	5.602	0.3	181714	0.95	0.16	0.937	6.89423	85	1.37855E-06
	4.488	0.2	190670	0.44	0.15	0.67	7.56148	84.4	1.02724E-06
	3.006	0.2	197424	0.48	0.08	0.601	6.90607	83.9	9.47532E-07
	3.439	0.3	248034	0.63	0.11	0.823	5.5515	82.5	1.41435E-06
	2.473	0.2	191437	0.51	0.08	0.658	5.89718	82.5	1.12562E-06
E3	3.586	0.5	211548	1.61	0.14	0.64	3.54498	81.6	1.15151E-06
	2.26	0.2	214823	0.4	0.09	0.467	7.56873	84.2	7.2085E-07
	5.17	0.3	202900	0.71	0.31	1.003	9.44637	79.9	1.97947E-06
	2.385	0.1	223523	0.33	0.08	0.278	8.43831	84.3	4.27147E-07
	4.391	0.6	209604	1.77	0.2	1.08	5.50306	83.9	1.70911E-06
	2.632	0.2	190772	0.48	0.1	0.542	7.36086	85.4	7.7778E-07
	3.692	0.2	214209	0.45	0.17	0.609	10.8625	85.9	8.4424E-07
	2.188	0.1	214772	0.36	0.11	0.235	7.42467	88	2.78181E-07
	2.484	0.2	195378	0.44	0.08	0.453	5.72493	84.9	6.69084E-07
F1	2.801	0.2	144870	0.55	0.19	0.682	9.57465	86.2	9.25508E-07
	4.284	0.3	164572	0.79	0.13	0.838	6.84392	84.2	1.30142E-06
	2.886	0.2	153928	0.54	0.15	0.459	7.6481	84.9	6.81782E-07
	3.175	0.2	165800	0.44	0.16	0.531	9.90618	89.1	5.70255E-07
	4.672	0.3	183505	0.69	0.22	0.941	11.1976	84.6	1.42056E-06
	4.067	0.3	166260	0.63	0.13	0.955	6.35811	81.7	1.71146E-06
	7.532	0.3	175369	0.64	0.11	1.291	5.76219	77.6	2.8342E-06
	3.596	0.2	169535	0.52	0.25	0.714	12.0886	86.2	9.66668E-07
	6.69	0.5	170763	1.11	0.14	1.661	6.86053	81.7	2.98828E-06
F2	3.818	0.1	110328	0.3	0.11	0.401	9.58841	89.2	4.25568E-07
	3.472	0.3	99480	0.72	0.17	1.013	6.86021	83.4	1.64483E-06
	4.979	0.3	123122	0.69	0.12	1.298	6.75791	82.2	2.26261E-06
	2.799	0.1	118618	0.38	0.11	0.312	6.97441	84	4.88839E-07
	1.646	0.1	85663	0.28	0.1	0.185	11.1758	88.2	2.14711E-07
	5.573	0.2	100299	0.53	0.16	1.123	15.7806	89.7	1.138E-06
	3.687	0.2	116316	0.61	0.09	0.757	6.25873	82.8	1.27739E-06
	3.711	0.2	133459	0.55	0.08	0.825	6.28958	86	1.13491E-06
	3.875	0.3	159198	0.71	0.18	0.859	8.91426	85.6	1.21492E-06
F3	5.842	0.4	125322	0.73	0.16	1.612	7.89829	83.1	2.66728E-06
	3.663	0.1	121996	0.37	0.12	0.348	10.0975	89.9	3.4322E-07
	5.107	0.4	157407	0.68	0.17	1.622	11.7227	83.5	2.6162E-06
	3.336	0.2	123429	0.43	0.11	0.638	6.8373	85.8	8.91393E-07
	3.833	0.3	137245	0.66	0.22	1.179	10.9468	85.3	1.70373E-06
	2.247	0.1	145177	0.41	0.11	0.457	8.69953	88.1	5.34442E-07
	6.008	0.5	122559	1.17	0.07	1.284	3.0882	74	3.27775E-06
	3.983	0.2	127676	0.56	0.17	0.748	11.3406	87.1	9.44002E-07
	2.604	0.2	126857	0.58	0.2	0.321	7.83563	87.1	4.04449E-07

Department of Mechanical Engineering, Master’s Degree Programme
Blekinge Institute of Technology, Campus Gräsvik
SE-371 79 Karlskrona, SWEDEN

Telephone: +46 455-38 55 10
Fax: +46 455-38 55 07
E-mail: ansel.berghuvud@bth.se